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ESTIMATION OF GROUND-WATER TRAVEL TIME AT THE HANFORD SITE: DESCRIPTION, PAST WORK, AND FUTURE NEEDS

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EXECUTIVE SUMMARY

The time for a contaminant to travel from a source to the biosphere is only one component of evaluating the consequences of ground-water contamination in the unconfined aquifer at the Hanford Site. The three components necessary for evaluating consequences of contamination are 1) the location of contaminant outflow to the biosphere, 2) the time of contaminant arrival at the outflow location, and 3) the quantity of contaminants reaching the outflow location. This report focuses on one component, the contaminant arrival time or travel time, because variations in estimates of this parameter at the Hanford Site have generated considerable interest.

Travel time is generally defined as the average length of time for ground water or contaminants to move from point A to point B along a particular flow path in a ground-water system. A number of interrelated factors influence contaminant movement (and travel times) in the unconfined aquifer at the Hanford Site. These factors include the pattern of natural and artificial recharge, the distribution of hydraulic properties in the aquifer, the position of contaminant flow paths, the chemical composition of liquid effluents discharged to the ground, geochemical behavior of contaminants in the ground water, and future conditions in the aquifer.

Many different estimates of ground-water and contaminant travel times have been made for the unconfined aquifer at the Hanford Site. In this report, estimates of travel time for the unconfined aquifer based on ground-water monitoring data, local measurements of velocity, and modeling are reviewed. This review demonstrates that rather than a single travel time for the unconfined aquifer, estimates of travel time depend on the starting locations, conditions in the aquifer, and whether the estimate is for ground water or a specific contaminant.

It is necessary to evaluate ground-water contamination at the Hanford Site in terms of outflow locations, distributions of arrival times, and outflow quantities. Establishing these arrival time and outflow quantity distributions for contaminants in the unconfined aquifer requires additional characterization

and modeling. By evaluating ground-water contamination in the unconfined aquifer in these terms, confusion about ground-water travel times at Hanford can be avoided in the future.

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INTRODUCTION

The U.S. Department of Energy's Hanford Site is located in a rural region of southeastern Washington State and occupies an area of 580 square miles. The Site (Figure 1) lies about 200 miles northeast of Portland, Oregon, 170 miles southeast of Seattle, Washington, and 120 miles southwest of Spokane, Washington. The Columbia River flows through the northern edge of the Hanford Site and forms part of the eastern boundary. The southern boundary of the Site includes the Rattlesnake Hills, which exceed 3300 ft in elevation. Both confined and unconfined aquifers are present beneath the Site. The main geologic units present are the Columbia River Basalt Group, the Ringold Formation, and a series of glaciofluvial sands and gravels informally known as the Hanford sediments. The Hanford Project was established in 1943 and was originally designed, built, and operated to produce plutonium for nuclear weapons. As a result of the plutonium processing operations, most of which occur in the 200-East and 200-West Areas (Separations Area), liquid wastes have been generated and discharged to the ground. Travel times required for these wastes to reach the accessible environment, mainly the Columbia River, are of interest.

The travel time for contaminants from a source to the biosphere is only one component necessary to evaluate the environmental consequences of ground-water contamination. As described by Nelson (1978a), three components are needed to evaluate present and future consequences of ground-water contamination: 1) the location of contaminant outflow to the biosphere, 2) the time of contaminant arrival at the outflow location, and 3) the quantity of contaminants reaching the biosphere at the outflow location. These three components are interrelated and no single one can be used to evaluate the consequences of ground-water contamination.

Contaminant outflow at locations in the Hanford Site unconfined aquifer consists of transfer to the underlying confined aquifer(s), ground-water discharge to the river, and evapotranspiration by plants and trees near the river where the water table is near land surface. For estimates of travel time in the future, another postulated discharge boundary consists of withdrawal from a well. Evaluating the consequences of any environmental problem at the Hanford

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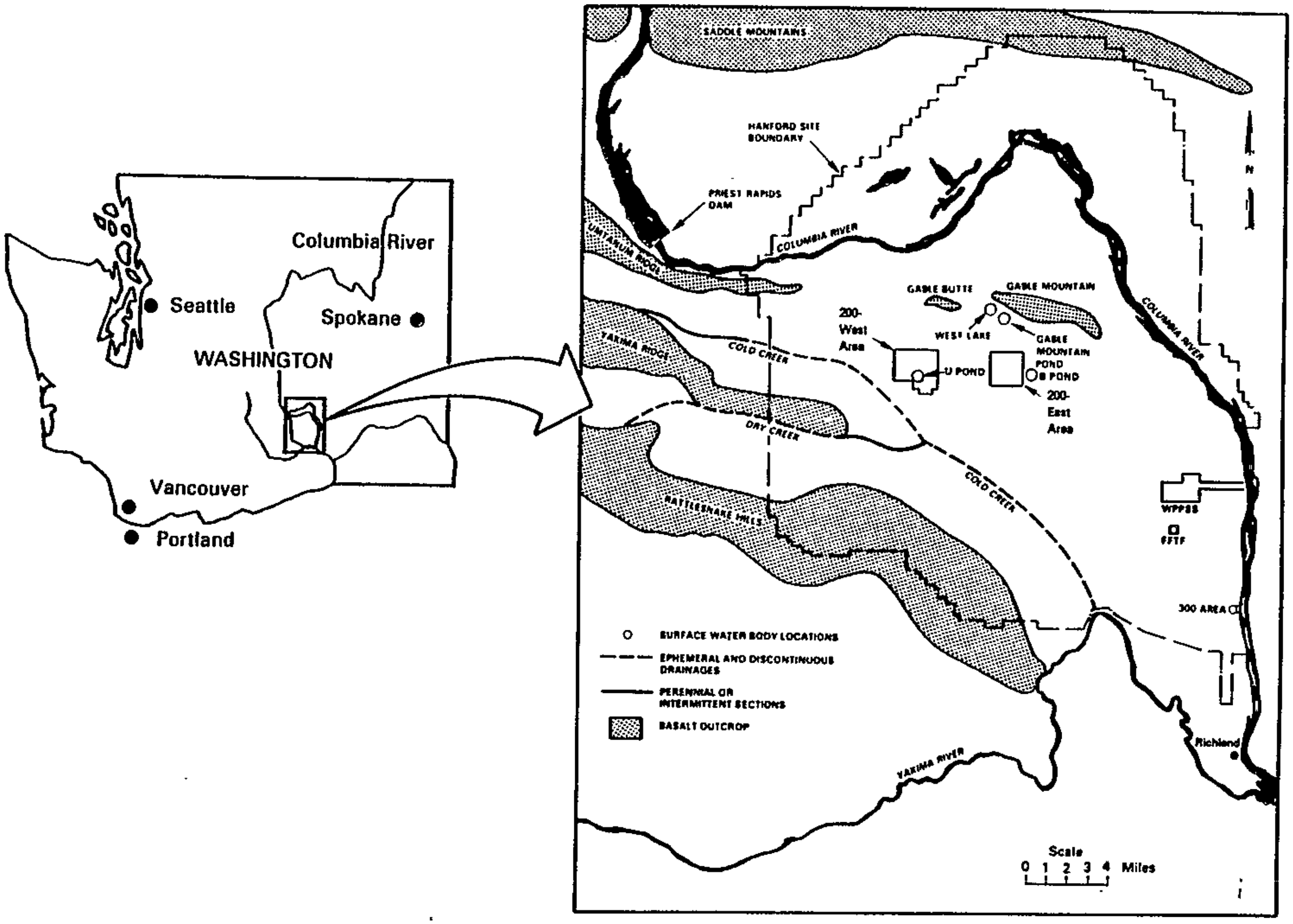

FIGURE 1. The Hanford Site

Site involves the careful determination of any present or future outflow locations for the contamination. The arrival time (or travel time) distribution suggested by Nelson (1978a) describes when contaminants will arrive at outflow locations. Nelson (1978a) states that the quantity of a contaminant reaching an outflow location is the most important item for evaluating the environmental consequences of ground-water contamination. Some contaminants do not pose a problem when present in ground water in small amounts, but large quantities may result in a serious hazard. However, other contaminants may be hazardous even in small quantities. Thus, the amount, concentrations, and type of contaminants in the ground water must be identified to evaluate the environmental consequences of any contamination. In addition, the mobility of a chemical constituent influences the consequences of ground-water contamination.

One component of determining the consequences of ground-water contamination is described in this report. Estimates of travel time for ground water and contaminants in the unconfined or water table aquifer at the Hanford Site that have been made since the early 1950s are reviewed and summarized. Many early estimates of travel time were based on ground-water velocity measurements and extrapolation of the existing ground-water monitoring data, resulting in wide variation in predictions. Because the variation in estimates of travel time for ground water and contaminants in the unconfined aquifer at Hanford has generated considerable confusion, the need for a document explaining these estimates at the Hanford Site was recognized. In addition, the summary of previous travel time estimates and the identification of future needs in this report establish a basis from which the consequences of ground-water contamination at the Hanford Site can be communicated within a scientifically defensible framework.

The report is divided into three sections. The first section includes a description of what is meant by travel time for ground water and contaminants, a discussion of the factors that influence travel time in the unconfined aquifer, and a description of how travel times are estimated. The second section provides a summary of past estimates of travel time in the unconfined aquifer. The final section provides a description of future needs for clarifying and improving estimates of travel time at Hanford. Most of the discussion is focused on determining travel times from locations within the 200-East and 200-West Areas. However, movement of contaminants from locations within the 100 Areas at the Site has also been investigated.

DESCRIPTION OF TRAVEL TIME

Travel time is generally defined as the average length of time for ground water or miscible contaminants to move from point A to point B along a particular flow path in a ground-water system. Variations between ground-water flow paths and hydrodynamic dispersion along each flow path tend to spread travel times and distribute contaminant particles. The first arrival of a contaminant has low concentration relative to the concentration at the source. Concentration along the flow path increases to some peak value and then decreases. Likewise, the distribution of contaminants will vary with time and distance along any outflow boundary where a collection of flow paths discharge to the biosphere. As a result, a distribution of contaminant travel times exists along any given flow path and along any given outflow boundary.

A pathline is the flow path or trajectory traced out by a particle of water or a contaminant (Fox and McDonald 1978). Pathlines may be associated with transient ground-water flow fields. Streamlines are lines drawn in a flow field so that they are tangent to the direction of flow at each point in the flow field at any given instant in time. In steady flow, the velocity at each point in a flow field remains constant with time, and the streamlines and pathlines coincide.

Different travel or arrival times can be determined from a distribution of contaminants. The first arrival of a contaminant at a point along a flow path needs to be distinguished from arrival of the peak or arrival of some other contaminant concentration. The first arrival may be important for contaminants that are hazardous in low concentrations, whereas arrival of the peak is important for determining the average travel time for a contaminant. Estimation of the first arrival requires that a contaminant concentration limit be specified, whereas the peak concentration is determined from the distribution of contamination at an outflow boundary. The total flux, which can be estimated from a distribution of contaminants, is important for determining the consequences of the contamination.

The distribution of a miscible contaminant resulting from dispersion along a flow path resembles a normal curve (Figure 2). Because of this similarity,

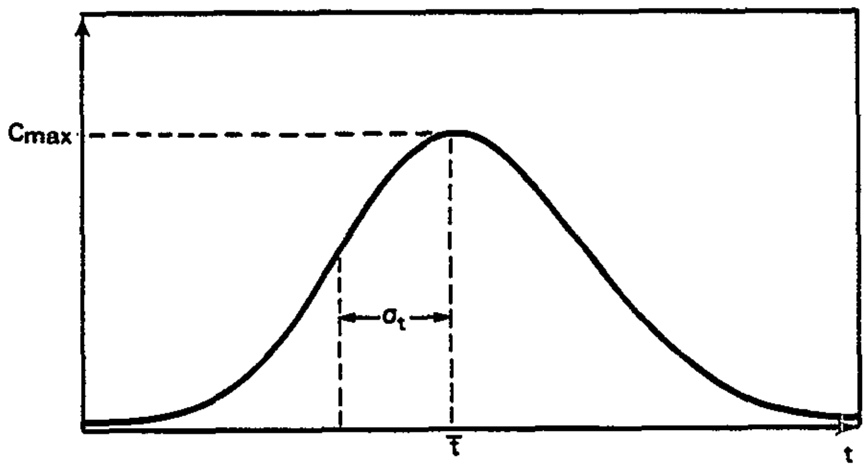

FIGURE 2. Distribution of Concentrations for a Miscible Contaminant at a Point Resulting from Hydrodynamic Dispersion Along a Flow Path Illustrated as a Normal Curve (after Levenspiel 1984)

the properties of the normal distribution can be used to describe the arrival distribution at a point along a flow path (Levenspiel 1984). The most useful measures for describing arrival distributions are the mean ($\bar{t}$) and variance (σ_t). The mean identifies when the center of mass of a distribution passes a measuring point. The variance of a tracer curve describes how spread out in time or how "fat" the distribution is.

INFLUENCES ON TRAVEL TIME AT THE HANFORD SITE

Contaminant movement and travel times in the unconfined aquifer at the Hanford Site are influenced by the pattern of natural recharge; the locations and volumes of artificial recharge resulting from large quantities of liquid effluents discharged to the ground over time in the operating areas, primarily the 200-East and 200-West Areas (Separations Area); the distribution of hydraulic properties within the unconfined aquifer; the starting and ending locations for flow paths; the chemical composition of liquid effluents and the geochemical behavior of contaminants in Hanford ground water; and conditions in the unconfined aquifer for computer simulations. These factors influencing movement of contaminants in the unconfined aquifer are interrelated. While one or more of these factors can control the velocity of the ground water or a contaminant at a specific location along a flow path, all may interact over the length of the flow path. The influence of each of these factors on travel time in the unconfined aquifer is discussed in this section.

The pattern of natural recharge to the unconfined aquifer at the Hanford Site affects the distribution of travel times by changing the elevation of the water table, altering the transmissivities, and influencing the hydraulic gradients in the aquifer. Natural recharge to the unconfined aquifer occurs as surface runoff from Rattlesnake Mountain and Umtanum Ridge to the south and west of the Site (Newcomb, Strand and Frank 1972), upward leakage from the lower basalt aquifers (Graham 1983), and direct recharge through the unsaturated zone (Gee and Kirkham 1984). The largest volume of natural recharge to the aquifer occurs from rainfall and snowmelt that contribute to infiltration in the Cold Creek and Dry Creek valleys to the west of the Hanford Site and west of the Rattlesnake Hills (Figure 1). During the past few years, recharge in the Cold Creek valley has increased from irrigation of wine grapes.

Evidence indicates that recharge occurs as a result of upward leakage from the confined aquifers to the unconfined aquifer (Dove et al. 1981). The West Lake basin, located north of the 200-East Area near Gable Mountain, is a discharge area for the lower confined aquifers (Graham 1983). An upward hydraulic gradient between the confined and unconfined aquifers exists over much of the

Hanford Site. However, there is evidence that the hydraulic gradients have been reversed and downward leakage has occurred around B Pond and Gable Mountain Pond near the 200-East Area (Graham, Last and Fetch 1984; Jensen 1987).

The climate at the Site is dry and mild, with approximately 16 cm of precipitation annually (PNL 1987). Most of the precipitation occurs during November, December, and January when the potential evapotranspiration is low and natural recharge can occur. Recharge to the unconfined aquifer is highly variable over the Site, and depends on soil conditions and vegetation patterns. Natural recharge at the Site has been measured at more than 10 cm/yr from a bare sandy soil and more than 5 cm/yr from a grass-covered field site (Gee and Kirkham 1984).

Artificial recharge to the unconfined aquifer occurs because large volumes of liquid effluents are discharged to the ground in and near the 200-East and 200-West Areas. The liquid effluents originate from chemical processing facilities in the Separations Area and consist primarily of cooling water and steam condensates. These liquid effluents are discharged to surface ponds, cribs, and ditches in the Separations Area (Graham et al. 1981). The major disposal ponds associated with the Separations Area are U Pond, B Pond, and Gable Mountain Pond (Figure 1). U Pond was deactivated in the fall of 1984 (Law et al. 1986), and deactivation of Gable Mountain Pond was completed in the fall of 1987. The liquid effluents have artificially recharged the unconfined aquifer and have created ground-water mounds beneath both the 200-East and 200-West Areas (Graham et al. 1981). This artificial recharge is believed to exceed the natural recharge entering the Separations Area as ground-water flow from the west by an order of magnitude (Graham et al. 1981). These mounds have altered ground-water flow in the unconfined aquifer (Figure 3). The flow direction, which was predominantly from west to east under pre-Hanford conditions (Newcomb, Strand and Frank 1972), is now highly variable within the Separations Area.

The locations and volumes of liquid effluents discharged to the ground at the Hanford Site also have changed with time (Graham et al. 1981). These changes in the location and magnitude of artificial recharge are reflected in

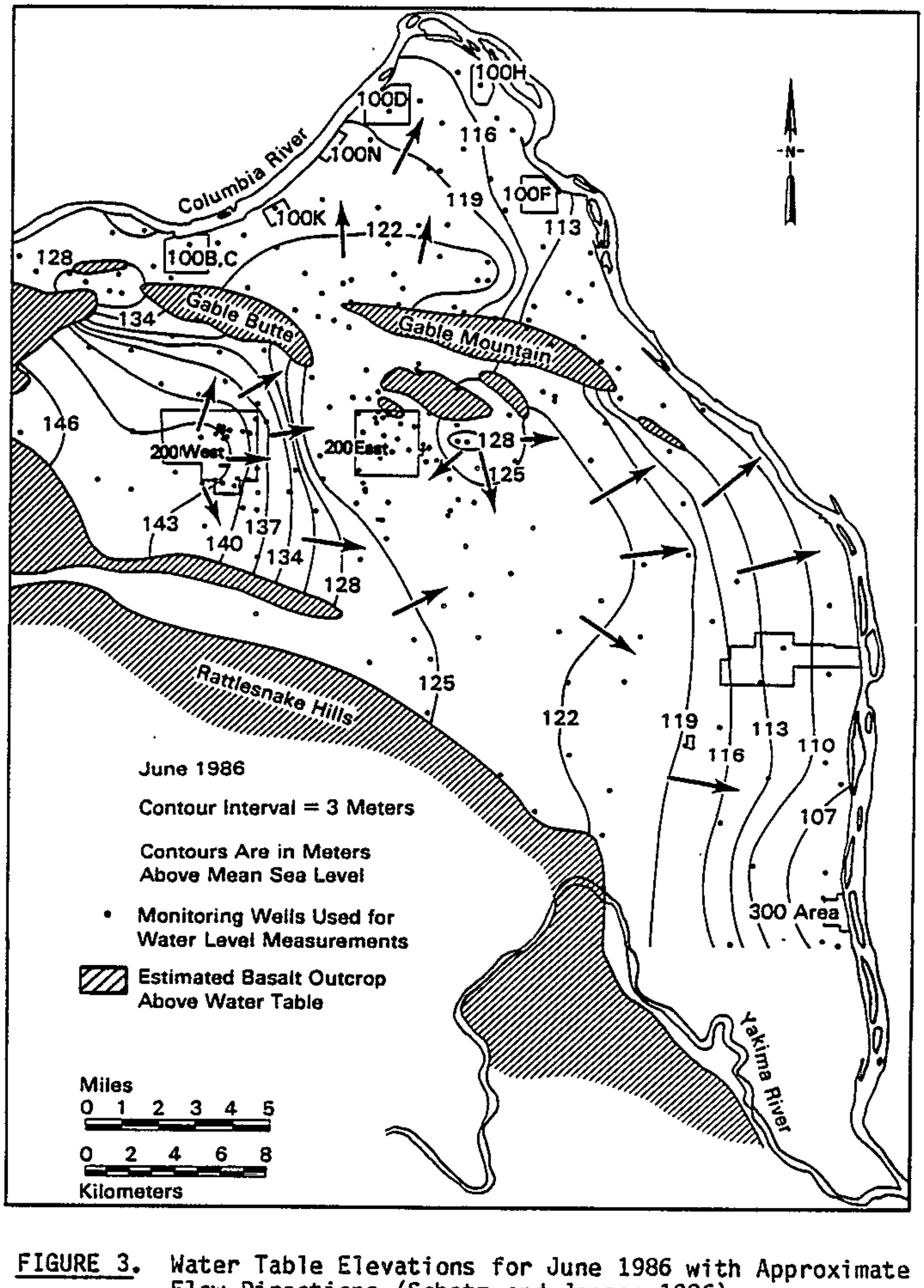

FIGURE 3. Water Table Elevations for June 1986 with Approximate Flow Directions (Schatz and Jensen 1986)

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water levels measured in wells at the Site (Zimmerman et al. 1986). Figure 4 illustrates the hydrograph for a well that responded to changes in discharge to B Pond. The water table changes for the period from 1944 to 1973 are documented by Kipp and Mudd (1974). Changes since 1973 are documented in Zimmerman et al. (1986) and in various environmental monitoring reports (e.g., PNL 1987).

The distribution of hydraulic conductivity in the unconfined aquifer also influences ground-water flow and contaminant movement at the Hanford Site (Davis and DeWiest 1966). The unconfined aquifer is located within the Ringold Formation, which consists of sediments ranging in size from clay to gravel, and the Hanford sediments, which are glaciofluvial sands and gravels overlying the Ringold Formation (Figure 5). The hydraulic conductivity, which describes the ability of the aquifer to transmit water, is more than an order of magnitude higher for the Hanford sediments than for the Ringold Formation (Graham et al. 1981).

FIGURE 4. Hydrograph for Well 699-45-42

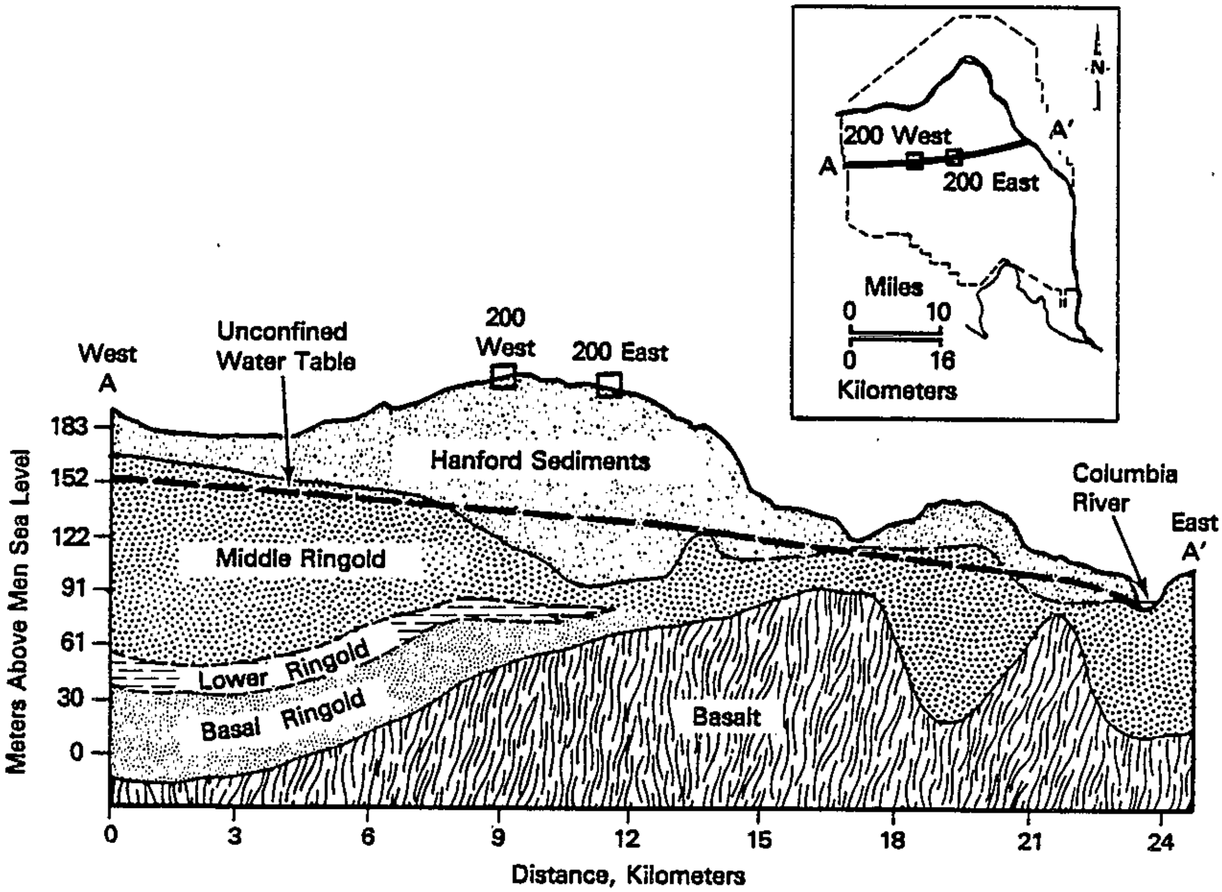

FIGURE 5. Generalized Cross Section for the Hanford Site (after Tallman et al. 1979)

The difference in aquifer properties between the Hanford sediments and the Ringold Formation is reflected in the ground-water mounding beneath the 200-East and 200-West Areas (Graham et al. 1981). By 1979, the water table beneath U Pond had risen more than 85 ft as a result of disposal operations in the 200-West Area. At the same time, the mound under B Pond near the 200-East Area had risen more than 30 ft. The B-Pond mound, although receiving about the same total volume of liquid effluents as the U-Pond mound, is less than one half the height of the mound beneath U Pond. The heights of the two mounds differ because the water table beneath the 200-West Area is located in the Ringold Formation, whereas mounding in the aquifer in the 200-East Area extends into the Hanford sediments, which are more permeable than the Ringold Formation. The resulting hydraulic gradient is steeper near the 200-West Area than near the 200-East Area. Ground-water velocities are much slower within the the 200-West Area than in the 200-East Area, so that travel times in the unconfined aquifer from waste sites in the 200-West Area are generally longer.

The distribution of hydraulic conductivity varies across the Hanford Site (Cearlock, Kipp and Friedrichs 1975). The aquifer properties can be expected to change along any given flow path, resulting in different velocities along the length of each path. Because the velocities vary along each individual flow path, local measurements of velocity cannot be extrapolated along an entire flow path.

The large volumes of liquid effluents discharged to the ground interact with aquifer properties and the existing ground-water flow system to influence flow paths in the unconfined aquifer. Consequently, the starting location for a flow path is critical for estimating travel time for ground water or contaminants. The flow path that ground water or a contaminant will follow depends on where, with respect to the ground-water mounds beneath the 200-East and 200-West Areas, the water or contaminant enters the unconfined aquifer. For example, the current mounding from B Pond has created a ground-water divide within the 200-East Area that separates flow directions from the 200-East Area to the north and south. Effluents introduced to the aquifer to the north of the ground-water divide will follow a flow path north through the gap between Gable Mountain and Gable Butte (Figure 3). Effluents introduced to the aquifer south of the ground-water divide will follow a flow path to the southeast (Figure 3).

The ending location of a flow path is also important for determining the travel time for ground water or contaminants. An estimate of travel time depends on whether the contaminant is transported to the Columbia River or to a hypothetical domestic well downgradient of the starting location; the latter is of interest from a regulatory standpoint.

The geochemical behavior of a chemical constituent also influences its movement in the ground water. Contaminants such as nitrate and tritium, which are present in high-volume liquid effluents at the Hanford Site, have a widespread distribution in the unconfined aquifer because they are not retained by the sediments comprising the aquifer (Price 1986). Radionuclides such as ^{90}Sr, ^{137}Cs, and $^{239,240}Pu$ are attenuated or retained by the sediments through adsorption, chemical precipitation, and ion exchange (Routson 1973; Ames and Rai 1978). In addition, these radionuclides are concentrated in small-volume liquid effluents. Therefore, the distributions of these attenuated radionuclides in the unconfined aquifer are limited when compared with the distributions of nitrate and tritium in the aquifer.

In addition to considering the impacts from past and current Site operations on flow paths and travel times, some estimates of travel time from locations within the 200 Areas have been made for post-Hanford conditions, when Site operations have ceased (DOE 1987). The water table for postoperational conditions is not only different from that currently observed, but is different from that considered to exist in the 1940s before operations at the Hanford Site began. Other post-Hanford conditions that have been considered and also influence the water table include farming practices, long-term climatic changes, and a proposed dam on the Hanford reach of the Columbia River. The resulting flow paths and travel times for post-Hanford conditions will not be the same as those observed today.

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REVIEW OF PREVIOUS TRAVEL TIME ESTIMATES AT THE HANFORD SITE

Because many thousands of pages of documents have been published on Hanford Site geohydrology, the list of documents reviewed for this report likely does not include all of the travel time estimates made at the Site. However, those travel times discussed represent the estimates made at the Site during more than 40 years of operations.

Travel times for ground water and contaminants in the unconfined aquifer at the Hanford Site have been estimated by methods that range from simple to complex. Simple methods have consisted of reviewing historical monitoring data and observing the arrival of detectable concentrations of contaminants at monitoring wells. Travel times have also been estimated by simple calculations with measured gradients and aquifer properties. More complex methods, consisting of applications of ground-water flow and contaminant transport models, have also been used. Most of the predictions of contaminant movement and travel time at the Hanford Site have been made in two dimensions.

The estimates of travel time described in this report are summarized in Table 1. Travel times estimated from ground-water monitoring data are discussed first, followed by estimates based on local measurements and modeling. The estimates of travel time are discussed in chronological order. The ground-water conditions at the time of the estimate and/or the assumptions necessary for the estimate are also discussed. Whenever radionuclide concentrations are included, they are discussed in the same units as the original reference so that the figures mostly appear as published.

ESTIMATES OF TRAVEL TIME FROM GROUND-WATER MONITORING DATA

One of the first ground-water travel times estimated at the Hanford Site was based on a review of limited monitoring data (Parker 1948). An average travel time of 10 years was predicted for underground water associated with "Hanford cribbed wastes" to reach the river, although there was no reference to the specific flow path considered. The travel time was predicted for ground water; the contamination front was speculated to move slower. Parker (1948)

TABLE 1. Summary of Ground-Water Travel Time Estimates Made at the Hanford Site

Reference	Starting Location	Comments
Parker (1948)	200 Areas	Travel time for radionuclides based on review of limited ground-water monitoring data
Parker (1954)	200 Areas	Travel time estimates for radionuclides based on extrapolation of limited ground-water monitoring data
Honstead, McConiga and Raymond (1955)	North of Gable Mountain	Gable Mountain site used to evaluate different techniques for measuring local ground-water velocities
Earth Sciences Personnel (1956)	200 Areas	Ground-water contamination (cesium-137) outside the 200 Areas confirmed for the first time after 10 years of disposal operations
Parker (1956)	200-East Area	Local velocities measured by borehole dilution tests, then extrapolated
Brown (1957b)	Southeast of the 200-East Area	Local velocities estimated from fluorescein dye tracer test
Bierschenk and McConiga (1957)	Southeast of the 200-East Area	Local velocities estimated from appearance of trace radionuclide concentrations
Bierschenk (1959)	200 Areas	Travel time estimates based on flow paths drawn on a water table map and calculations of average ground-water velocity
Brown and Haney (1964)	PUREX cribs (200-East Area)	Travel time for tritium from the PUREX cribs estimated following discovery of tritium as a product of uranium fission
Eliason (1966b)	216-A-10 Crib (200-East Area)	Travel time from the 216-A-10 crib downgradient 2 miles to a monitoring well estimated from observations of beta activity

TABLE 1. (contd)

Reference	Starting Location	Comments
Cearlock and Mudd (1970)	100-N Area	Travel times estimated with a ground-water flow model and used to define water arrival distribution curves
Arnett (1975)	Selected monitoring wells	Changes in streamlines and travel times used to evaluate the impacts of additional cooling water disposal to Gable Mountain Pond, based on a predicted 1980 table
Gephart (1976)	Selected monitoring wells	Changes in streamlines and travel times used to evaluate the impacts of a proposed aquaculture project, based on a predicted 1980 water table
Friedrichs, Cole and Arnett (1977)	200 Areas	Flow paths and travel times predicted with the Hanford Pathline Calculational (HPC) program, Water table conditions were transient through 1995
Arnett, Brown and Baca (1977)	200-East Area	Arrival time and outflow quantity distributions at the Columbia River, based on a predicted 1980 water table
Arnett et al. (1977)	U Pond (200-West Area)	Changes in streamlines and travel times were used to evaluate the impacts of increasing irrigation in the Cold Creek Valley. Contaminant movement from locations in the 200-East Area were predicted. Both were based on a predicted 1980 water table
Myers (1978)	PUREX cribs (200-East Area)	First arrival of the 30-pci/ml isopleth at the Columbia River from the 200-East Area demonstrated with ground-water monitoring data

TABLE 1. (contd)

Reference	Starting Location	Comments
Graham et al. (1981)	200 Areas	Travel time estimates based on measured flow path lengths and velocities determined from observed tritium movement
Murthy et al. (1983)	200 Areas	Radionuclide transport calculations made to assess the implications of removing interstitial liquids from single-shell tanks. Predictions were based on a 1980 water table surface
DOE (1987)	200 Areas	The VTT and TRANSS codes were applied to evaluate alternatives for disposal of high-level defense wastes with future conditions of 0.5 and 5 cm/yr recharge
U.S. Geological Survey (USGS 1987)	PUREX cribs (200-East Area)	Travel time estimate based on review of ground-water monitoring data. Also reviewed travel time estimates made by SEARCH Technical Services

calculated that a conservative travel time of 5 years would not significantly increase concentrations of radionuclides in the Columbia River from Hanford operations.

The next reference to travel time estimated from ground-water monitoring data at the Hanford Site was also made by Parker (1954). Average travel times of 100 and 1500 years along different flow paths to the Columbia River were predicted for contaminants from waste disposal sites in the 200 Areas. Parker (1954) indicated that these travel times were 10 to 150 times greater than the estimates made during early operation of the disposal sites. These travel times were based on extrapolation of limited ground-water monitoring data showing trace amounts of ruthenium, uranium, and nonradioactive ions such as nitrate and calcium.

Contamination of ground water outside the 200-East and 200-West Areas was confirmed for the first time in 1956 after 10 years of disposal operations.

(Earth Sciences Personnel 1956). The contamination was identified as ^{137}Cs, and a 35-ft/day ground-water velocity was estimated from movement of the cesium. Travel times estimated from this ground-water velocity would represent the first arrival of contaminants.

In the early 1960s tritium was discovered as a product of uranium fission (Haney, Brown and Reisenauer 1962). This discovery prompted the analysis of waste streams from the Plutonium Uranium Extraction (PUREX) and the Reduction Oxidation (REDOX) separations plants and monitoring of the ground water near the discharge facilities for tritium. The lowest level of detection for tritium at the time of its discovery as a fission product was 10,000 pCi/L (Haney, Brown and Reisenauer 1962). In 1963, improved analytical techniques lowered the detection limit to 2000 pCi/L. The current detection limit for tritium used in the Pacific Northwest Laboratory's (PNL's) ground-water monitoring project is 300 pCi/L (Price 1986).

Brown and Haney (1964) estimated travel time for tritium from the PUREX cribs based on early monitoring data (Figure 6). Their measurements of travel time were based on the first arrival of gross beta emitters (^{106}Ru and ^{106}Rh) and tritium in monitoring wells located at various distances from the PUREX cribs, which began receiving discharges in 1955 (DOE 1987). Brown and Haney (1964) estimated a travel time of 7 to 8 years for ^{106}Ru to move from the PUREX plant site southeast to the Columbia River, and a travel time for tritium of 6 to 7 years. They also estimated a travel time of 20 years from the 200-West Area to the river for "radiocontaminants" discharged to the ground from the REDOX plant, which began operating in 1951.

Brown and Haney (1964) identified three sources of uncertainty for their estimates of travel time to monitoring wells and the river: 1) the variation of radionuclide concentrations with depth, 2) the relatively sparse network of monitoring wells at some locations, and 3) possible inaccuracies in the interpretation of the ground-water flow system. They stated that their philosophy for interpreting the monitoring data to estimate arrival times was to err on the conservative side when anomalies were evident.

Each of the sources of uncertainty for their estimates of travel time was explained by Brown and Haney (1964). They recognized that the tritium

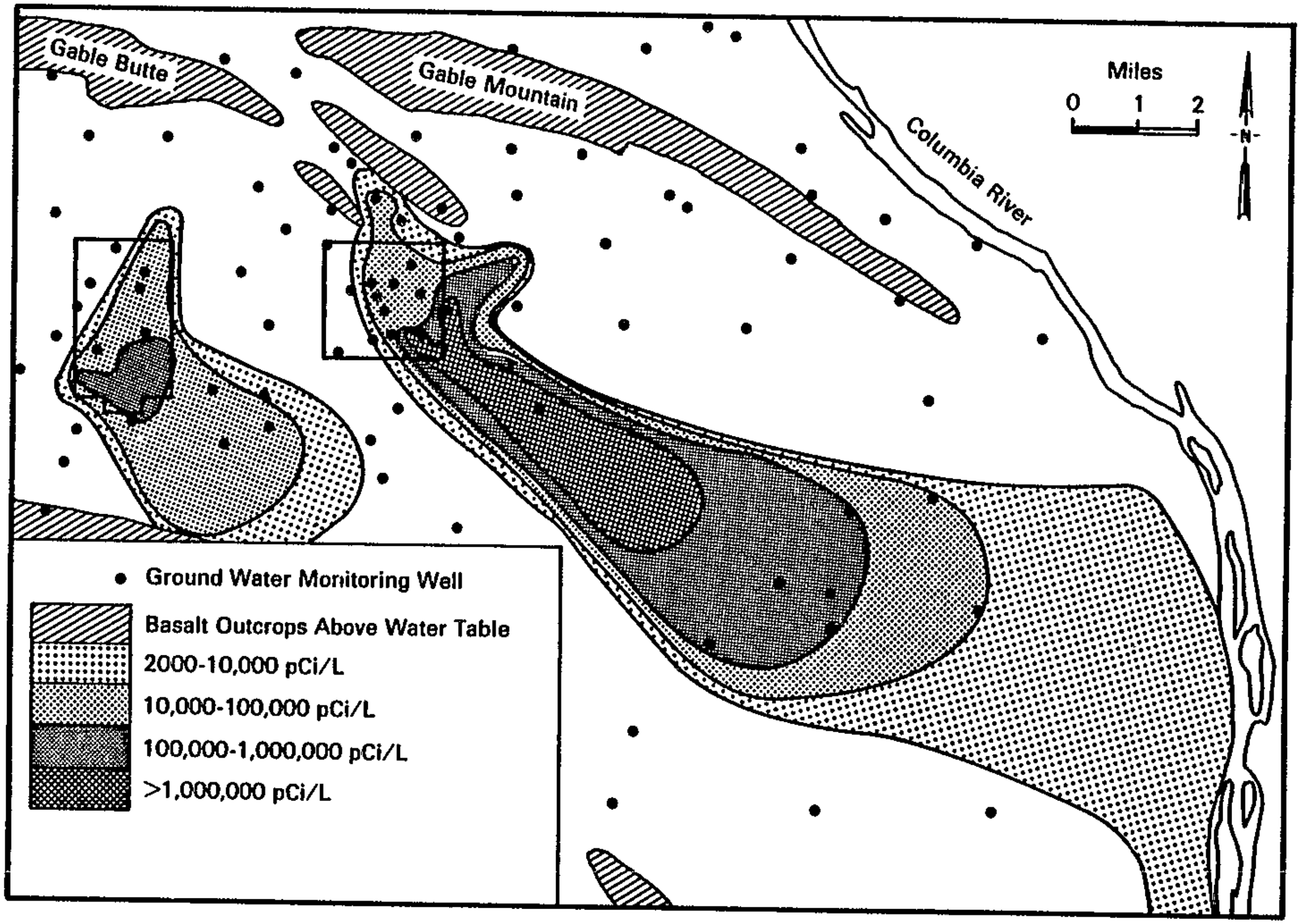

FIGURE 6. Extent of Tritium Measured in the Unconfined Aquifer During July - December 1963 (after Brown and Haney 1964)

concentrations varied with depth in the aquifer and that most of the monitoring wells were open to a large interval, making the monitoring results highly variable. The distribution of wells near the river at that time was sparse, making it difficult to interpret the monitoring data. Inaccuracies with interpretation of the ground-water flow system resulted from measurement of sporadic concentrations near the leading edge of the tritium plume, which produced uncertainty in the estimates of travel time for tritium. Brown and Haney attributed the sporadic measurements to the fact that the tritium concentrations were close to the detection limit and that fluctuations of the river may have influenced the concentrations.

The estimates of travel time by Brown and Haney (1964) for tritium and ruthenium moving from the 200-East Area were endorsed by Newcomb, Strand and Frank (1972) based on the fact that the water table to the east of the 200-East Area is in the more permeable glaciofluvial (Hanford) sediments. While they agree with Brown and Haney's estimate of travel times from the 200-East Area, Newcomb, Strand and Frank (1972) state that the times required to reach the Columbia River from the 200-West Area will be much longer than 20 years, "...at least many scores of years and probably over a hundred years." The reason given for this difference is the "100-fold" contrast of permeability between the gravels in the upper part of the Ringold Formation and the Hanford sediments.

The distribution of tritium in the unconfined aquifer reported by Eliason (1966a) is illustrated in Figure 7. The distribution in Figure 7 reflects refined analytical techniques for measuring tritium concentrations and changes in interpretation of ground-water monitoring data for the unconfined aquifer. Because tritium was reaching the Columbia River in lower concentrations than was previously thought, this different interpretation of the monitoring data was used to modify the previous travel time estimated by Brown and Haney (1964).

An average travel time for beta emitters from the 216-A-10 (A-10) crib downgradient southeast approximately 2 miles to well 699-39-39A was estimated by Eliason (1966b). In late 1962, an increase of beta activity in discharges to the A-10 crib was observed for a 2-month period. A maximum beta activity in

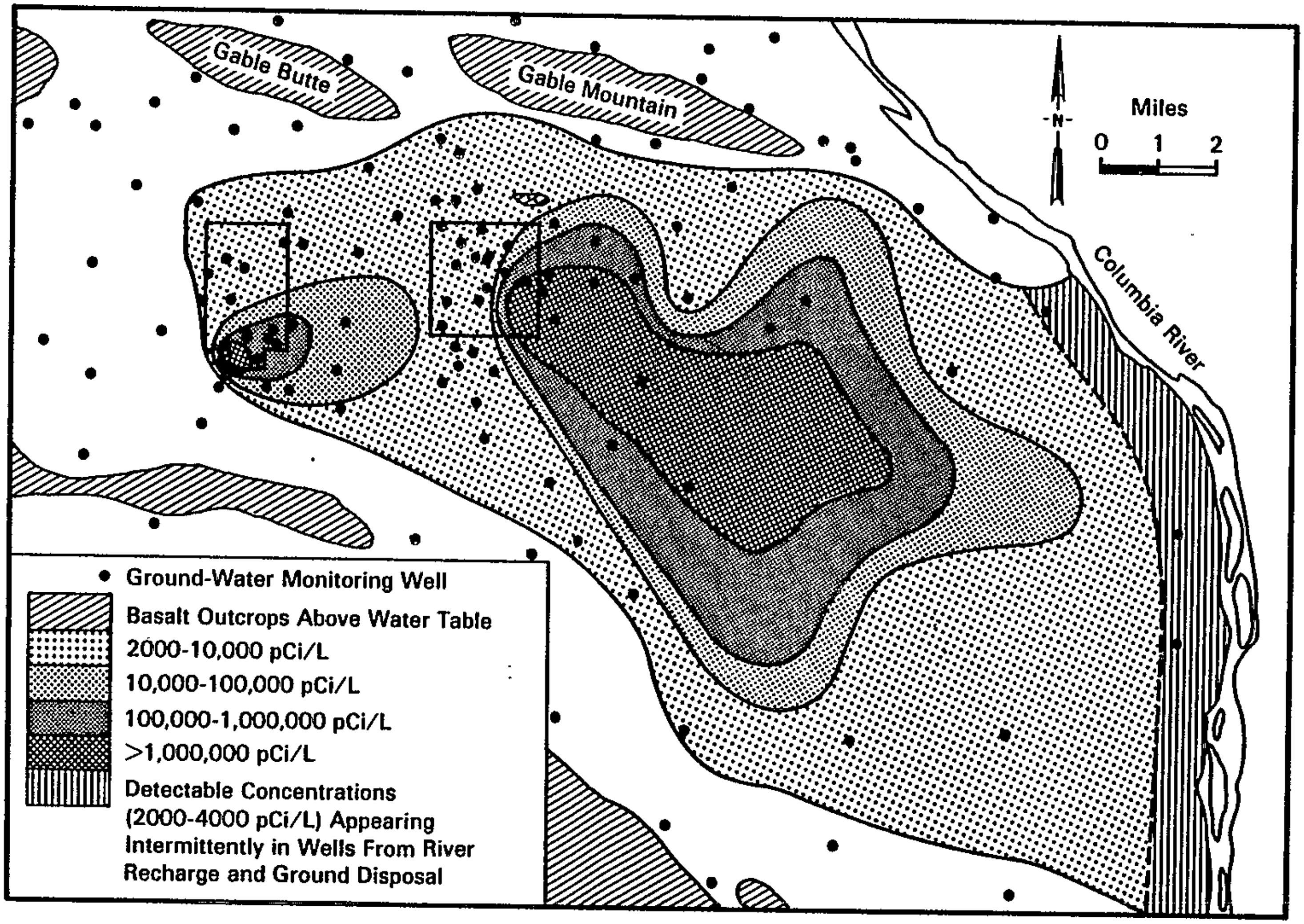

FIGURE 7. Extent of Tritium Measured in the Unconfined Aquifer During July - December 1965 (Eliason 1966a)

well 699-34-39A was observed in January 1965. The travel time for the beta activity from the A-10 crib to this well was estimated at 26 months. This prediction is comparable to an observed increase in tritium concentrations in the same wells during 1985 resulting from the restart of PUREX operations in 1983 (Price 1986).

Essig (1968) reported a much smaller areal extent of tritium contamination (Figure 8). Essig (1968) stated that some tritium was present beyond the 2000 pCi/L isopleth and some had probably reached the river, but the concentrations were too low to be measured in the ground water or in the river.

Myers (1978) mapped the 30 pCi/ml isopleth of the tritium plume (with the lower detection limit for tritium) as having reached the Columbia River (Figure 9). This interpretation was based on increasing concentrations in well 699-40-1. Eddy (1979), Eddy and Wilbur (1980), and subsequent monitoring reports also mapped the tritium plume as having reached the river. Myers (1978) also attempted to correlate gross beta peaks at wells 699-34-42 and 699-33-22 with disposal facilities in the 200-East Area. However, Myers indicated that the correlation was difficult because contaminant plumes from different release points coalesced, masking the true time of arrival for any one plume.

Based on observation of the ground-water monitoring data, the 30 pCi/ml isopleth of the tritium plume is estimated to have reached the Columbia River around 1976 to 1979. Assuming that most of the tritium in the ground water between the 200-East Area and the river is from PUREX operations, which began in 1956, the arrival of the 30 pCi/ml isopleth of the tritium plume at the river in 1976 to 1979 represents an average travel time of 20 to 23 years from the PUREX cribs. Average arrival time for a continuous source of a contaminant is represented by half the maximum sustained contaminant concentration at a point downgradient of the source. The travel time estimated from arrival of the 30 pCi/ml concentration, which is close to half the maximum sustained concentration in well 699-40-1 (Price 1986), therefore represents the average arrival time of the tritium plume.

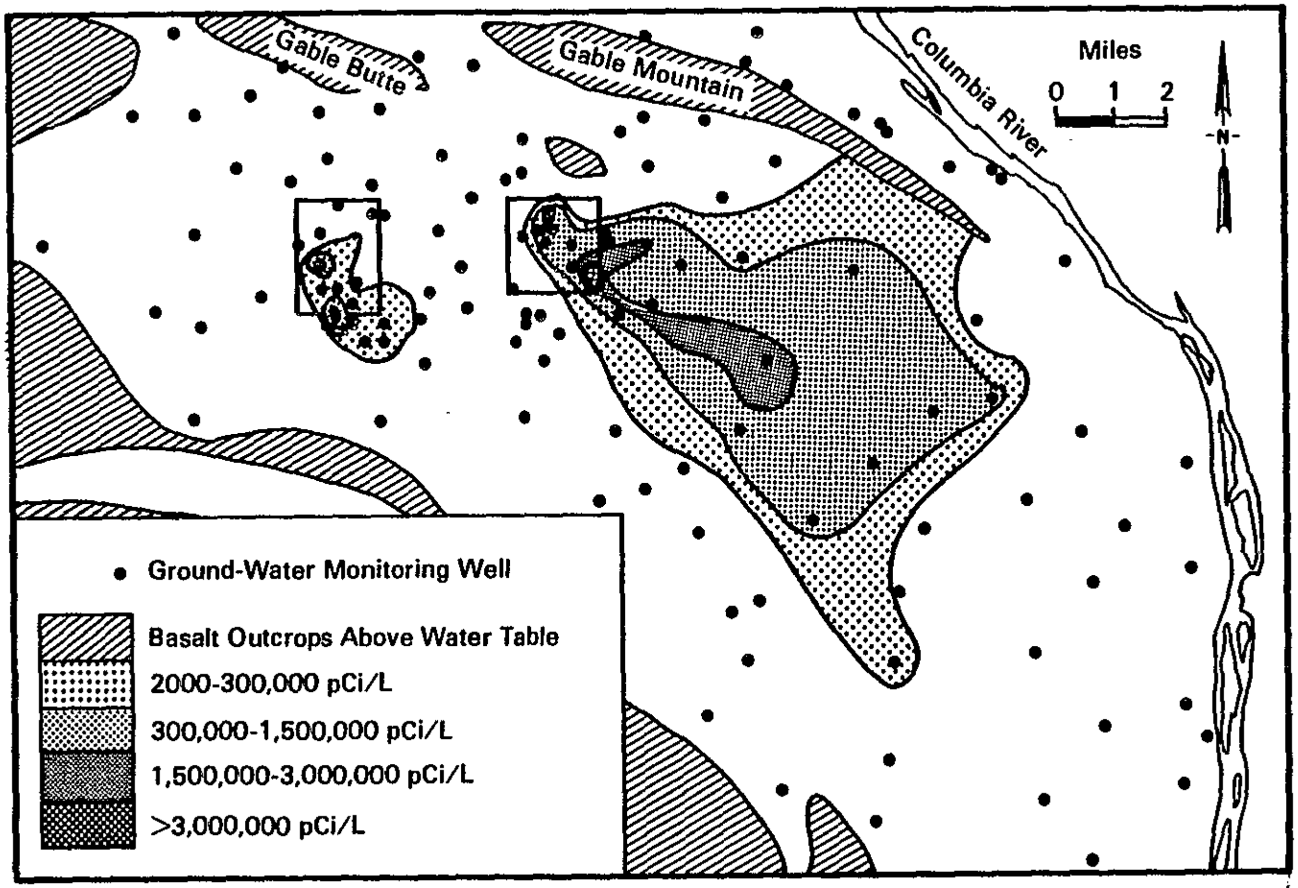

FIGURE 8. Extent of Tritium Measured in the Unconfined Aquifer During July - December 1967 (after Essig 1968)

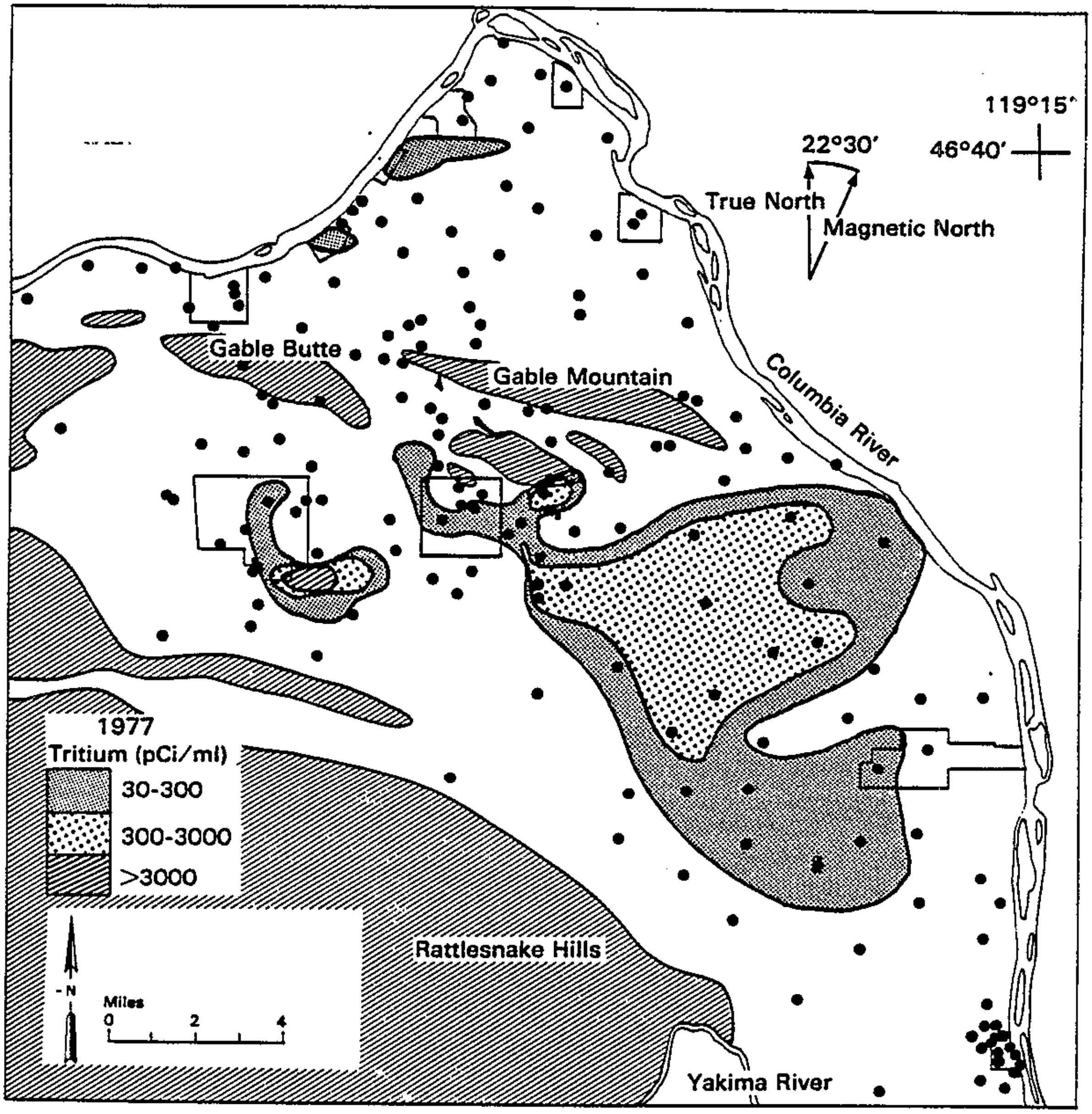

FIGURE 9. Extent of Tritium Measured in the Unconfined Aquifer During 1977 (after Myers 1978)

Graham et al. (1981) discuss an average travel time of 30 years from waste sites in the 200-East Area to the Columbia River and an 80-year average travel time from waste sites in the 200-West Area to the river. These estimates of travel time are based on flow velocities calculated from measured path lengths and observed tritium movement to the southeast of the 200-East Area.

Recently, the U.S. Geological Survey (USGS) reviewed work at the Hanford Site by an outside consulting firm (USGS 1987). The consulting firm, SEARCH Technical Services, Inc. (SEARCH), hypothesized that a high-permeability channel connects the 200-East Area with the Columbia River at the Old Hanford Townsite. SEARCH estimated that the travel time for ground water in this channel was on the order of 2.5 years. The USGS concluded that the available geologic, hydrologic, and water chemistry data neither confirm nor refute the existence of the hypothesized channel. However, the USGS stated that an alternative hypothesis to the channel is possible, namely broad areas of high permeability with a localized ground-water discharge near the Old Hanford Townsite (Figure 1).

The USGS reviewed the ground-water monitoring data and estimated that the average travel time for tritium from the PUREX cribs to the Columbia River was slightly longer than 13 years (USGS 1987). However, they determined that because of uncertainties in interpreting some of the data, it would be more appropriate if they stated that the travel time ranged from 10 to 20 years. They arrived at the 13-year average travel time by assuming, on the basis of discharge records, that most of the tritium was discharged to the aquifer at the PUREX cribs after 1963. An arrival time at the river of 1976 gives the 13-year estimate (Figure 10).

ESTIMATES OF TRAVEL TIME BASED ON LOCAL MEASUREMENTS

Local measurements of velocity at the Hanford Site have been extrapolated to estimate travel times from waste sites in the 200 Areas to the Columbia River. One difficulty with this extrapolation is that the ground-water velocity varies along any given flow path in response to changes in hydraulic

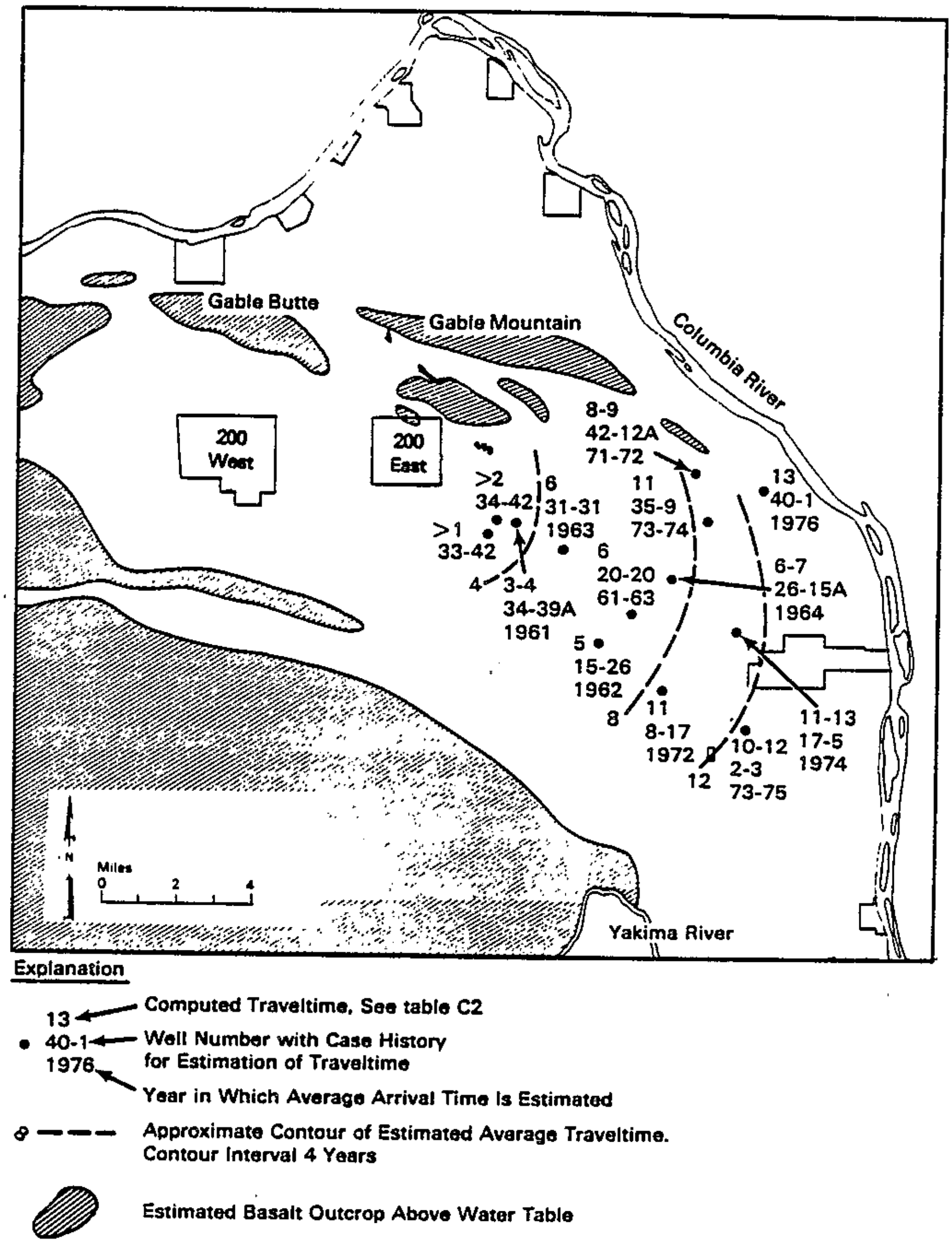

FIGURE 10. Average Travel Times for Tritium and Nitrate Moving from the 200-East Area to the Columbia River Estimated by the USGS (USGS 1987)

conductivity, effective porosity, or hydraulic gradient. The velocity at any given point along a flow path may not represent the average velocity, which, when integrated along the entire flow path, gives the travel time.

Local measurements for estimating travel time at the Hanford Site are based on observations of contaminant movement, tracer tests, or borehole dilution tests. Local observations of contaminant movement at the Site have been made near waste disposal facilities, mostly in high-permeability sediments near the 200-East Area. In tracer tests, a tracer is injected into the aquifer and observed in another well, either in an injection/pumping well pair or under natural hydraulic gradient conditions. Both pumping and natural gradient tracer tests have been performed in the Hanford unconfined aquifer. In borehole dilution tests, a tracer is added to a well and the rate of dilution from natural ground-water flow through the well is observed. Given knowledge of the aquifer conditions, information can be gained about the ground-water velocity near the well.

Honstead, McConiga and Raymond (1955) describe an extensive pumping and tracer test at a site immediately north of Gable Mountain. The pattern of wells used in the tracer test was established by the USGS for an aquifer test. The Gable Mountain test site was used to evaluate several different techniques for measuring ground-water velocities. A tracer test at the same location with fluorescein dye revealed a velocity of 170 ft/day under natural gradient conditions. Borehole dilution tests at the Gable Mountain site also demonstrated that most of the tracer moved near the water table.

Parker (1956) discusses measurements of velocity with borehole dilution tests in the unconfined aquifer near the 200-East Area. These local velocity measurements were extrapolated to give a 5-year travel time for 13 miles to the Columbia River. However, the water table near the 200-East Area is in the higher permeability Hanford sediments so that the local velocity is higher than the average velocity along the flow paths from the 200-East Area to the river.

Brown (1957a) discusses the results of an extensive borehole dilution testing effort. More than 70 borehole dilution tests were performed in the unconfined aquifer, with more than 200 measurements. Nearly 53 percent of the measurements were considered by Brown (1957a) to be invalid because of

1) improperly or inadequately perforated well casings, 2) plugged perforations, 3) imperfect mixing of the tracer solution (an electrolyte) with the well water, or 4) improper volume or concentration of tracer, resulting in density effects in the well. The results from borehole dilution tests were not used to extrapolate travel times.

Brown (1957b) describes a method for detecting fluorescein dye in water samples at low concentrations. The detection method was used in a natural gradient tracer test between wells southeast of the 200-East Area. Velocities up to 350 ft/day were measured with a reported confidence limit of 95 percent and velocities as high as 770 ft/day were reported with a confidence limit of 50 percent. The points at which these velocities were measured are in areas that have among the highest reported transmissivities in the unconfined aquifer (Cearlock, Kipp and Friedrichs 1975).

Bierschenk and McConiga (1957) describe appearance of "trace concentrations of radioactive materials" in wells southeast of the 200-East Area. The specific wells at which the concentrations were measured are not described in the report. However, these velocities were apparently on the order of hundreds of feet per day, similar to those observed during the fluorescein tracer test.

Bierschenk (1959) discusses the difference between a calculated average ground-water velocity and the velocity measured with fluorescein tracer tests. The flow rates based on the fluorescein dye were estimated to be as much as three times greater than a calculated average velocity, which was based on the average hydraulic gradient, average hydraulic conductivities for the different aquifer materials, and an assumed effective porosity of 10 percent. This comparison illustrates the difference between an average velocity and a local velocity measured at a point.

ESTIMATES OF TRAVEL TIME MADE WITH GROUND-WATER MODELS

One of the first travel times calculated for the unconfined aquifer was reported by Bierschenk (1959). Average travel times of about 180 years for a flow path from the 200-West Area to the Columbia River and 175 years for a flow path from the 200-East Area to the river were estimated. These travel times were based on calculations of average ground-water velocity in the aquifer and a flow path based on the presence of a "hydraulic barrier" resulting from disposal of wastewater to B Pond. When nitrate contamination appeared on its eastern side, the "barrier" was found to be the result of well casing survey errors (Haney 1960).

In the 1960s, attempts began to describe ground-water flow and contaminant transport in the unconfined aquifer at the Hanford Site with models. Nelson and Haney (1962) discuss the potential for applying electric analog models to describe ground-water flow in the unconfined aquifer. They determined that an electric analog would be useful for determining the flow path from any location on the project to the Columbia River and for evaluating the distributions of travel time along those flow paths. However, digital computers were used to represent ground-water flow in the unconfined aquifer instead of electric analogs.

The first ground-water flow and contaminant transport models were developed for the Hanford unconfined aquifer during the mid-1960s to the 1970s. Nelson (1965) and Cearlock (1971) discuss application of computer programs to evaluate transport of waste by ground water from locations in the unconfined aquifer to the Columbia River. Nelson (1965) identified the water travel time and distribution of contaminant arrival times as necessary for mathematical analysis of the flow system.

Predictions of ground-water flow and contaminant transport in the unconfined aquifer at the Hanford Site have been based on different models. The Variable Thickness Transient (VTT) code was developed to simulate two-dimensional ground-water flow in isotropic but heterogeneous aquifer materials based on the Boussinesq equation for unsteady flow (Kipp et al. 1972). The term isotropic indicates that the hydraulic properties of the aquifer are the same in all directions, whereas the term heterogeneous indicates that these properties may vary from point to point in space. The Boussinesq equation describes ground-water flow in unconfined, or phreatic, aquifers (Bear 1979). The VTT code was adapted to ground-water data from the Hanford unconfined aquifer and calibrated with a calculational procedure described by Cearlock, Kipp and Friedrichs (1975). The Multicomponent Mass Transport (MMT) code was developed to simulate the movement of radionuclides in saturated and unsaturated sediments (Ahlstrom et al. 1977). The MMT code, which simulates mass (contaminant) transport processes with a discrete-parcel random-walk algorithm, was developed to use the water movement patterns determined with the VTT code. The MMT code was also applied to Hanford data to simulate movement of the tritium plume between the 200-East Area and the Columbia River. These ground-water flow and contaminant transport models have been applied to a number of investigations at Hanford. Some of these investigations were based on analysis of ground-water and contaminant travel times.

Friedrichs, Cole and Arnett (1977) describe development and application of the Hanford Pathline Calculational (HPC) code that considers advective transport of a contaminant along a pathline or streamline. The ground-water flow model of the unconfined aquifer based on the VTT code provides the ground-water flow patterns for the HPC code, which was applied to predict pathlines and travel times from starting locations near the 200-West and 200-East Areas (Figure 11).

The starting locations in Figure 11 are not associated with any specific waste sites, but are located in circular patterns around the 200-West and 200-East Areas. The spacing between starting locations was based on conditions of equal flow originating from the ground-water mounds in each area. For these predictions, the ground-water model was applied to simulate the water table conditions from 1975 through 1995 under the influence of reduced wastewater discharges in the 200 Areas. For the simulations, pathlines were predicted until 1995 with the water table configuration predicted by the ground-water flow model. After 1995, a steady-state water table surface based on 1995 conditions was used to define streamlines beginning from the end points of the pathlines.

The resulting pathlines for starting locations near the 200-West Area are illustrated in Figure 12, and those for starting locations near the 200-East Area are illustrated in Figure 13. The average travel times to reach the Columbia River along flow paths starting near the 200-West Area are listed in Table 2. The travel times to reach the Columbia River listed in Table 2 range between 84 and 161 years. Average travel times to the Columbia River for the

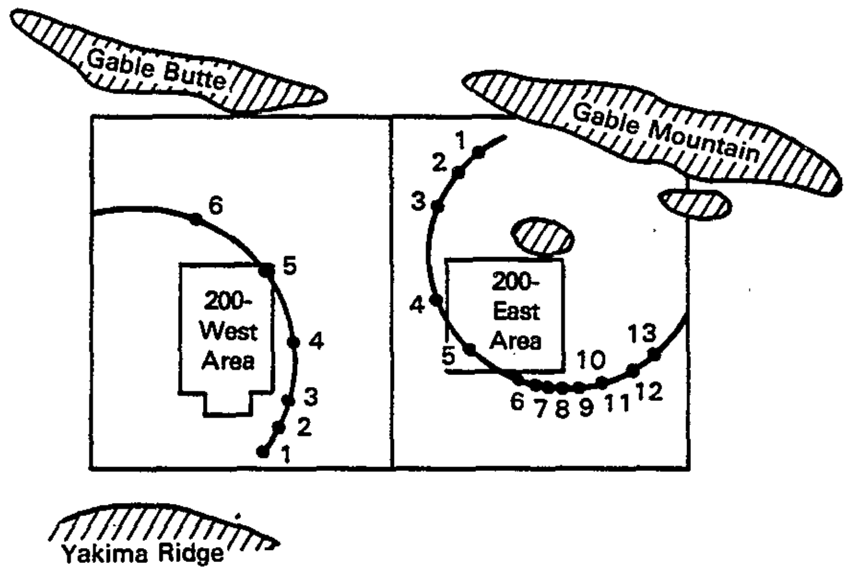

FIGURE 11. Selected Starting Locations and Pathline Numbers in the Hanford HPC Application (Friedrichs, Cole and Arnett 1977)

flow paths starting near the 200-East Area are listed in Table 3. These travel times range from 27 years to reach the Columbia River near the Old Hanford Townsite and 209 years to reach the river along a more southern flow path.

Friedrichs, Cole and Arnett (1977) concluded that predictions of contaminant movement in the Hanford unconfined aquifer can be significantly improved by analyzing pathlines, which account for transient flow conditions, rather than streamlines, which describe steady-state conditions. The pathline approach accounts for variations in the flow paths in response to changing water table conditions. A recent modification of the streamline approach applied to predicting flow paths and contaminant transport in the Hanford unconfined aquifer is included in the TRANSS code, which is documented by Simmons, Kincaid and Reisenauer (1986).

Cearlock and Mudd (1970) applied a streamline analysis to evaluate performance of a waste disposal crib in the 100-N Area of the Hanford Site. The crib is located close to the river, and for the low Columbia River level and steady-state conditions simulated, the average travel times predicted

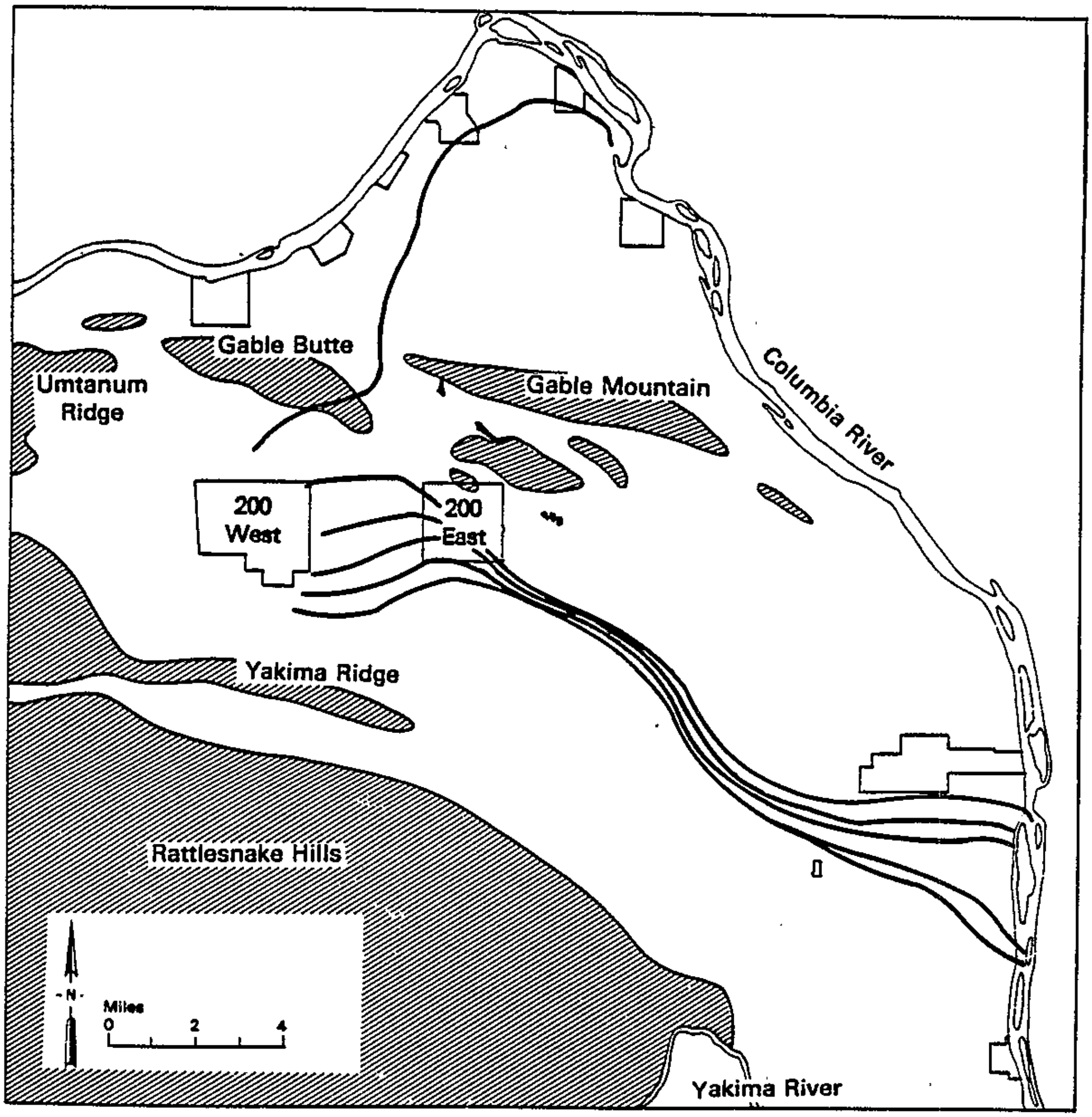

FIGURE 12. Pathlines (see Figure 11 for pathline numbers) from Near the 200-West Area (Friedrichs, Cole and Arnett 1977)

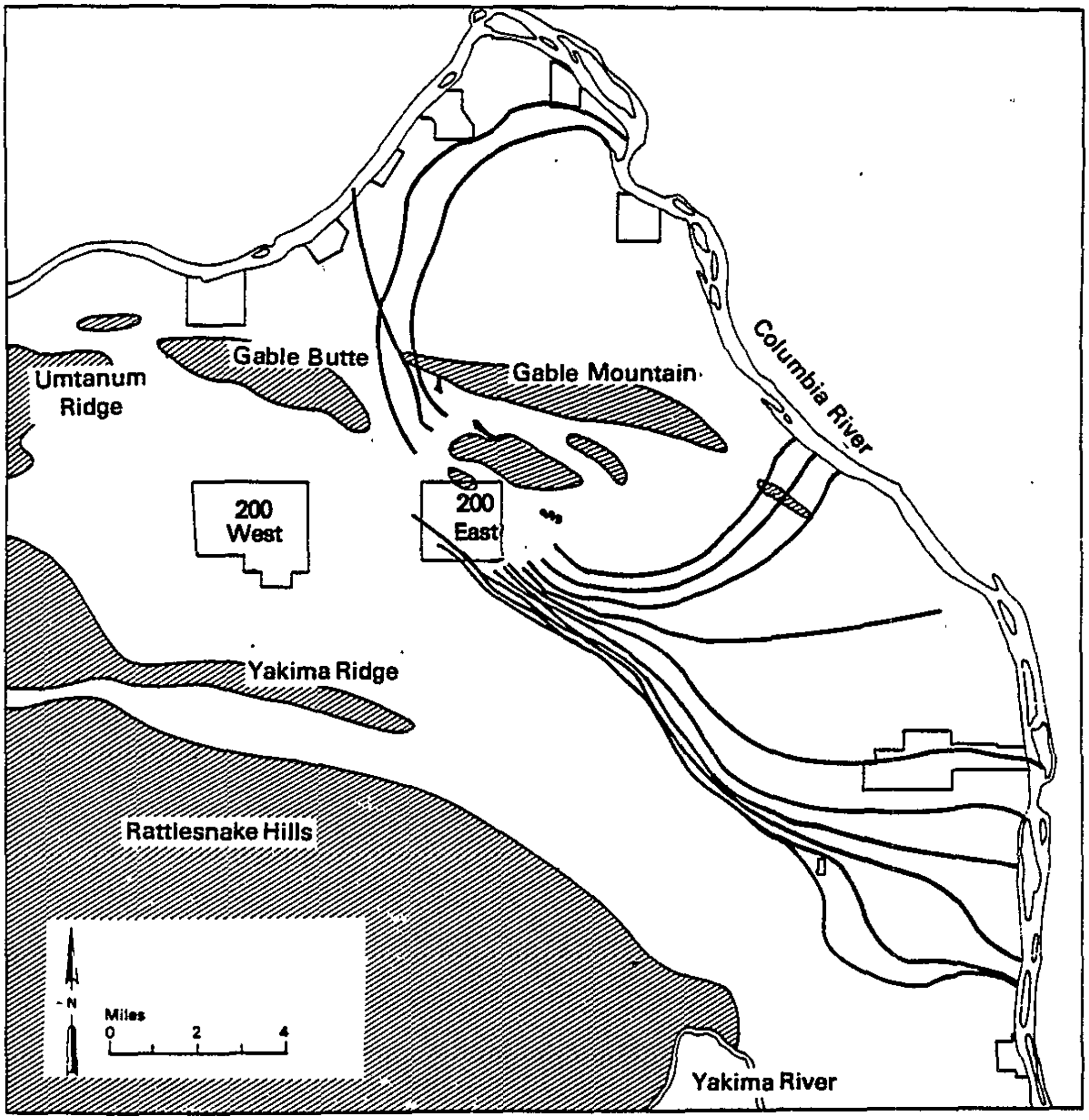

FIGURE 13. Pathlines (see Figure 11 for pathline numbers) from Near the 200-East Area (reported by Friedrichs, Cole and Arnett 1977)

TABLE 2. Average Travel Time Versus Distance for the 7 Pathlines Originating Near the 200-West Area (see Figures 11 and 12) (Friedrichs, Cole and Arnett 1977)

Pathline Number	Total Distance, ft	Total Time, yr
1	105,600	161
2	104,261	144
3	98,572	84
4	98,475	84
5	103,200	129
6	70,244	139

TABLE 3. Average Travel Time Versus Distance for the 14 Pathlines Originating Near the 200-East Area (see Figures 11 and 13) (Friedrichs, Cole and Arnett 1977)

Pathline Number	Total Distance, ft	Total Time, yr
1	51,048	43
2	31,082	43
3	63,487	81
4	96,357	209
5	95,263	125
6	82,691	125
7	76,104	71
8	74,129	71
9	70,556	162
10	52,106	246
11	45,594	39
12	41,573	27
13	38,443	31

from the crib to the river were on the order of several to tens of days. These travel times were used to define water arrival curves (Figure 14) for the different scenarios considered. The curves represent the distribution of travel times from the waste disposal crib to the Columbia River.

Arnett (1975) compared predicted water levels, steady streamlines from selected wells monitoring the unconfined aquifer, and average travel times to evaluate the impacts of additional cooling water disposal to Gable Mountain Pond. The streamlines were based on a predicted 1980 water table. Arnett (1975) concluded that the streamlines (Figure 15) and travel times would not be adversely affected by the additional discharges to Gable Mountain Pond. In most cases, the average travel times from specific wells (Table 4) were predicted to increase because of changes in the streamlines resulting from the additional discharges.

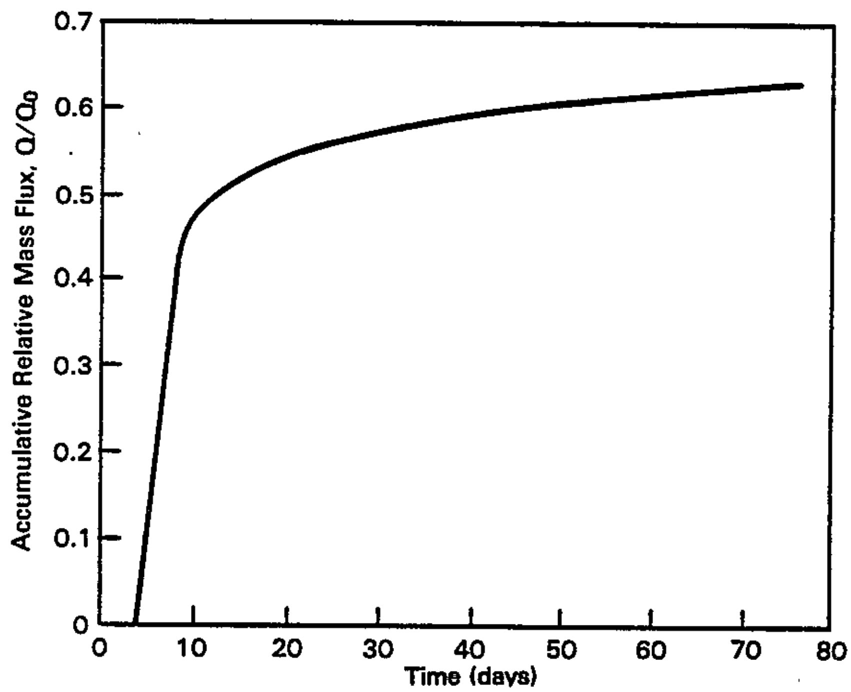

FIGURE 14. Water Arrival Time at the Columbia River from the 1301-N Crib (from Cearlock and Mudd 1970)

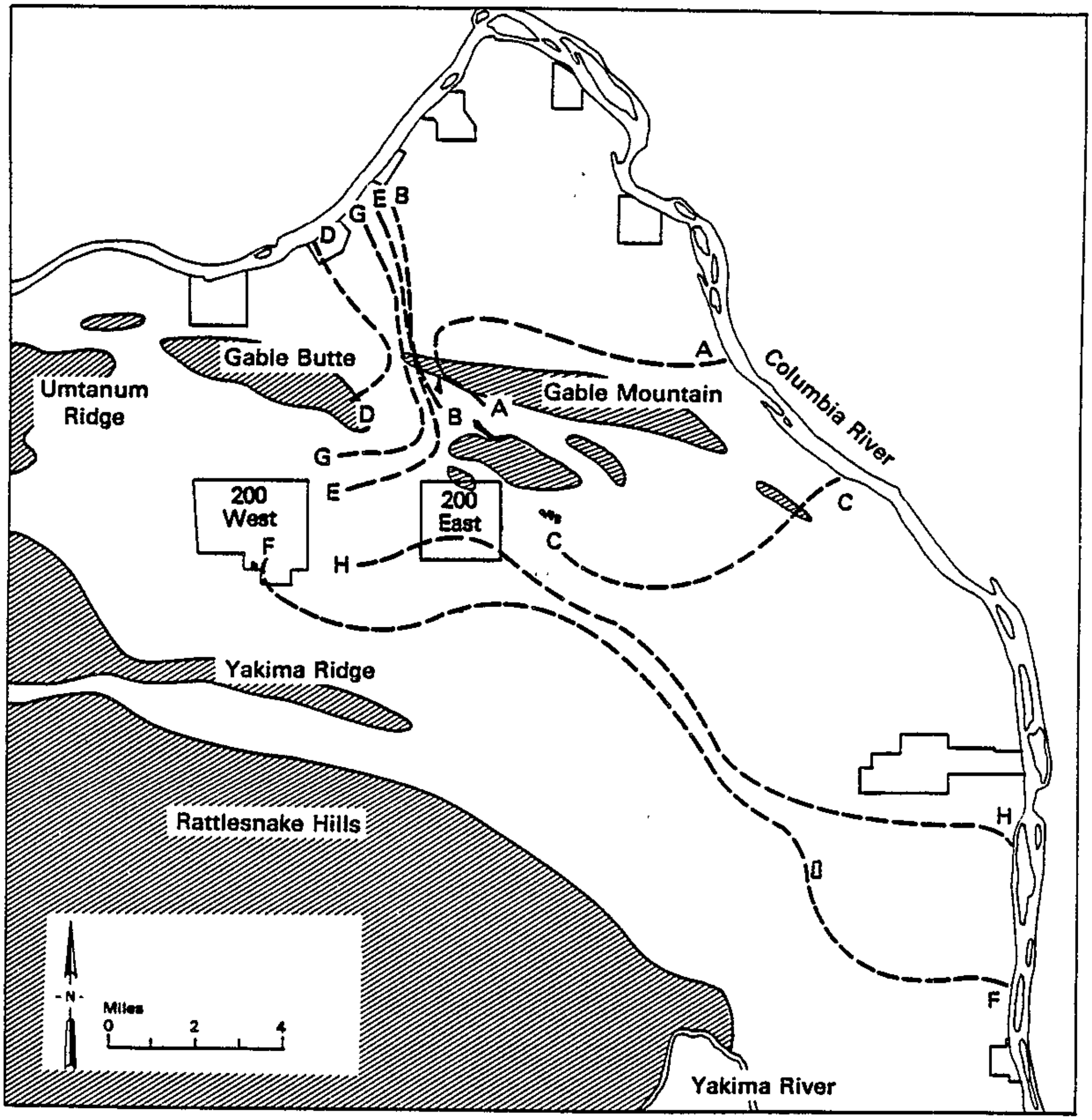

FIGURE 15. Steady Streamlines from Selected Wells for a Predicted December 1980 Water Table Surface Without Additional Cooling-Water Discharge to Gable Mountain Pond (after Arnett 1975)

TABLE 4. Average Travel Times Along Streamlines (see Figure 15) with and Without Additional Discharge to Gable Mountain Pond (from Arnett 1975)

Well Number	Map Letter	3.8×10^9 L/yr Additional Discharge, yr	No Evaporator Discharge, yr
699-55-50A	A	30	20
699-54-57	B	15	25
699-37-43	C	30	30
699-55-70	D	55	55
699-45-69	E	95	40
699-35-78	F	140	145
699-48-71	G	60	50
699-35-70	H	120	75

Gephart (1976) investigated the impacts to the unconfined aquifer of a proposed aquaculture project located west of the Hanford Site in the Cold Creek Valley. Steady streamlines and average travel times from four well sites were compared to assess the impacts of the proposed aquaculture project (Figure 16). The streamlines for estimating travel times were based on a the crib to the predicted 1980 water table surface. The water disposal from the proposed project was predicted to have a small impact on the streamlines and travel times from these locations (Table 5).

Arnett et al. (1977) applied the HPC code to investigate the impacts of increased irrigation in the Cold Creek Valley. A predicted 1980 water table surface was used to predict steady streamlines from starting locations surrounding U Pond in the 200-West Area to the Columbia River (Figure 17). The increased irrigation was predicted to have only minimal impact on the streamlines and average travel times from these starting positions (Table 6). Arnett et al. (1977) also applied the HPC code to predict contaminant movement from a hypothetical high-level waste tank leak in the 200-East Area. The streamline to the Columbia River for investigating the impact of the tank leak was based on a predicted 1980 water table surface (Figure 18). An average travel time of 125 years was estimated for the 17.5-mile streamline.

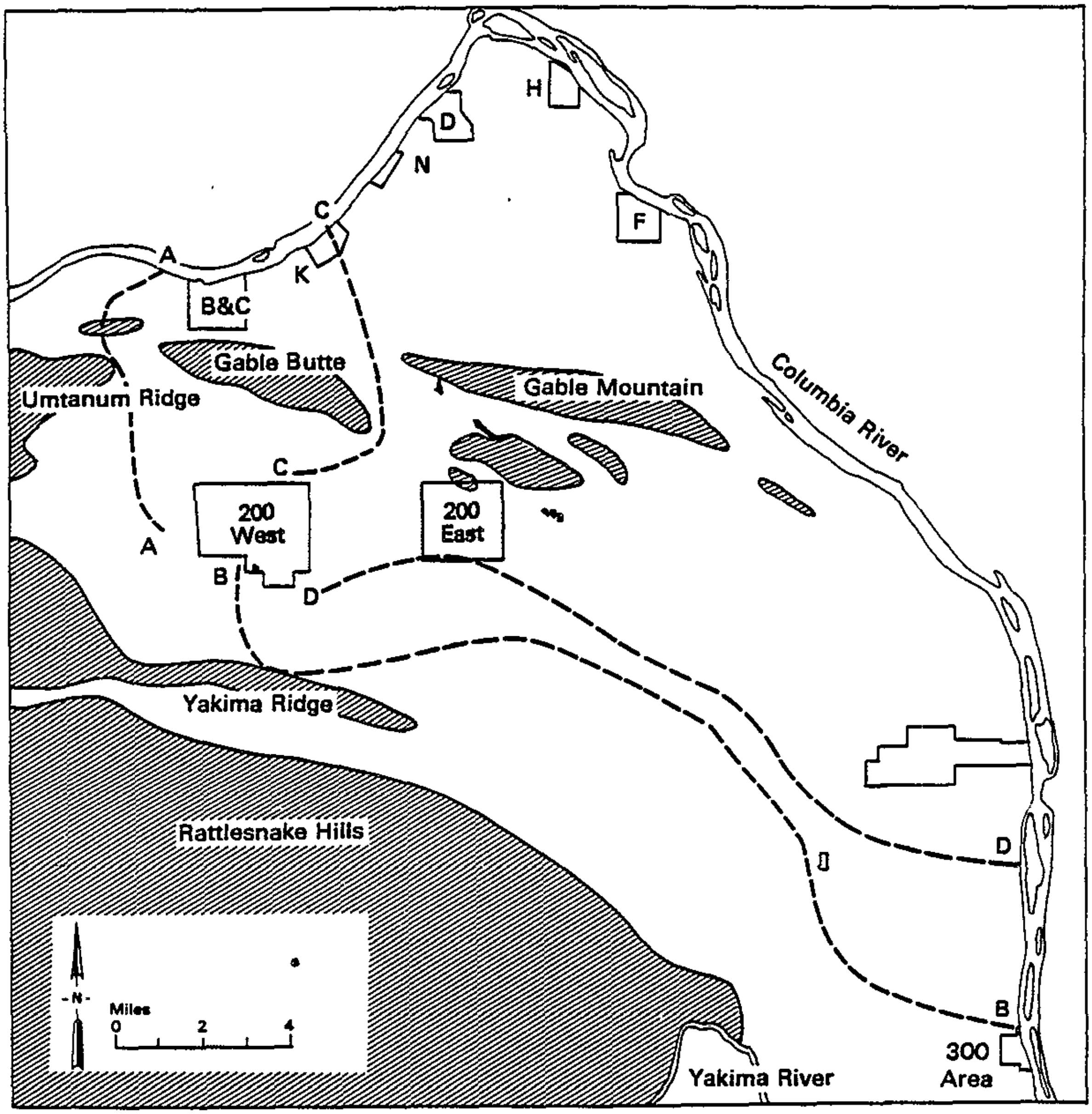

FIGURE 16. Steady Streamlines from Selected Wells for a Predicted December 1980 Water Table Surface Without Proposed Aquaculture Water Discharge (after Gephart 1976)

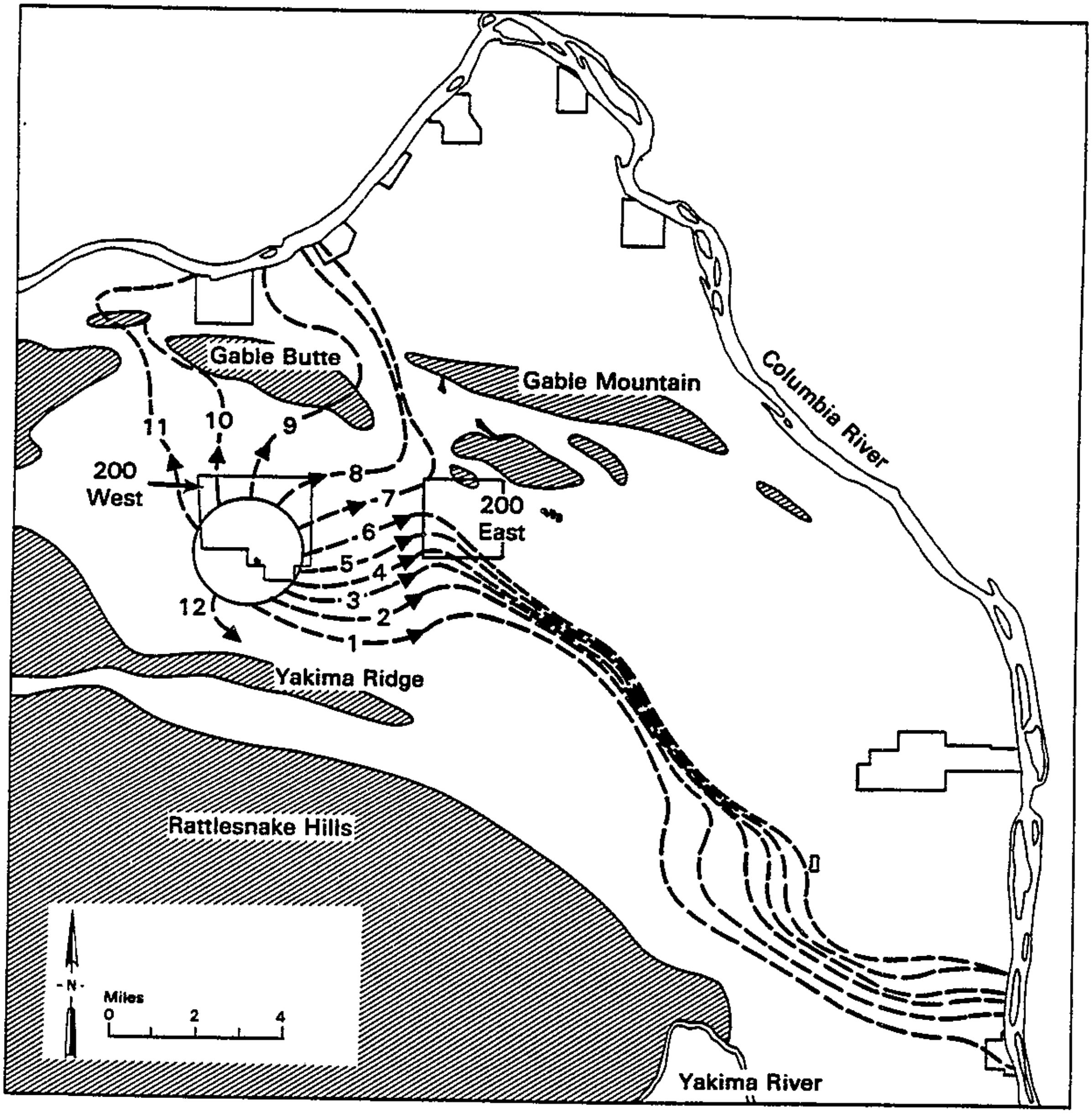

FIGURE 17. Steady Streamlines from Near the 200-West Area to Evaluate the Impacts of Increased Irrigation in the Cold Creek Valley (after Arnett et al. 1977)

TABLE 5. Average Travel Times Along Streamlines (see Figure 16) for Determining the Impact of Proposed Aquaculture Waste Discharge (from Gephart 1976)

Well Number	Map Letter	3.8×10^9 L/yr Additional Discharge, yr	No Evaporator Discharge, yr
699-43-89	A	282	224
699-35-78	B	218	212
699-48-71	C	54	55
699-35-70	D	78	80

TABLE 6. Comparison of Average Travel Times and Distances Along Streamlines (see Figure 17) for Determining the Impacts of Irrigation in the Cold Creek Valley (from Arnett et al. 1977)

	Travel Time, yr		Travel Distance, yr	
Streamline	Nonirrigated	Irrigated	Nonirrigated	Irrigated
1	130	122	23.5	23.6
2	81	79	22.4	22.3
3	71	70	21.6	21.6
4	69	70	21.5	21.4
5	83	89	21.5	21.4
6	121	136	21.5	21.4
7	43	41	9.8	9.8
8	63	59	9.1	9.2
9	108	109	8.2	8.5

Most of the applications of ground-water flow and transport models for investigations at the Hanford Site during the early to middle 1970s were based on predictions of flow paths and travel times. More recently, however, these models have been applied to predict not only the distribution of arrival times but also the distributions of contaminant quantities at outflow locations. These predictions of contaminant arrival and quantity distributions have been primarily for radionuclides, and have been used to estimate dose to individuals.

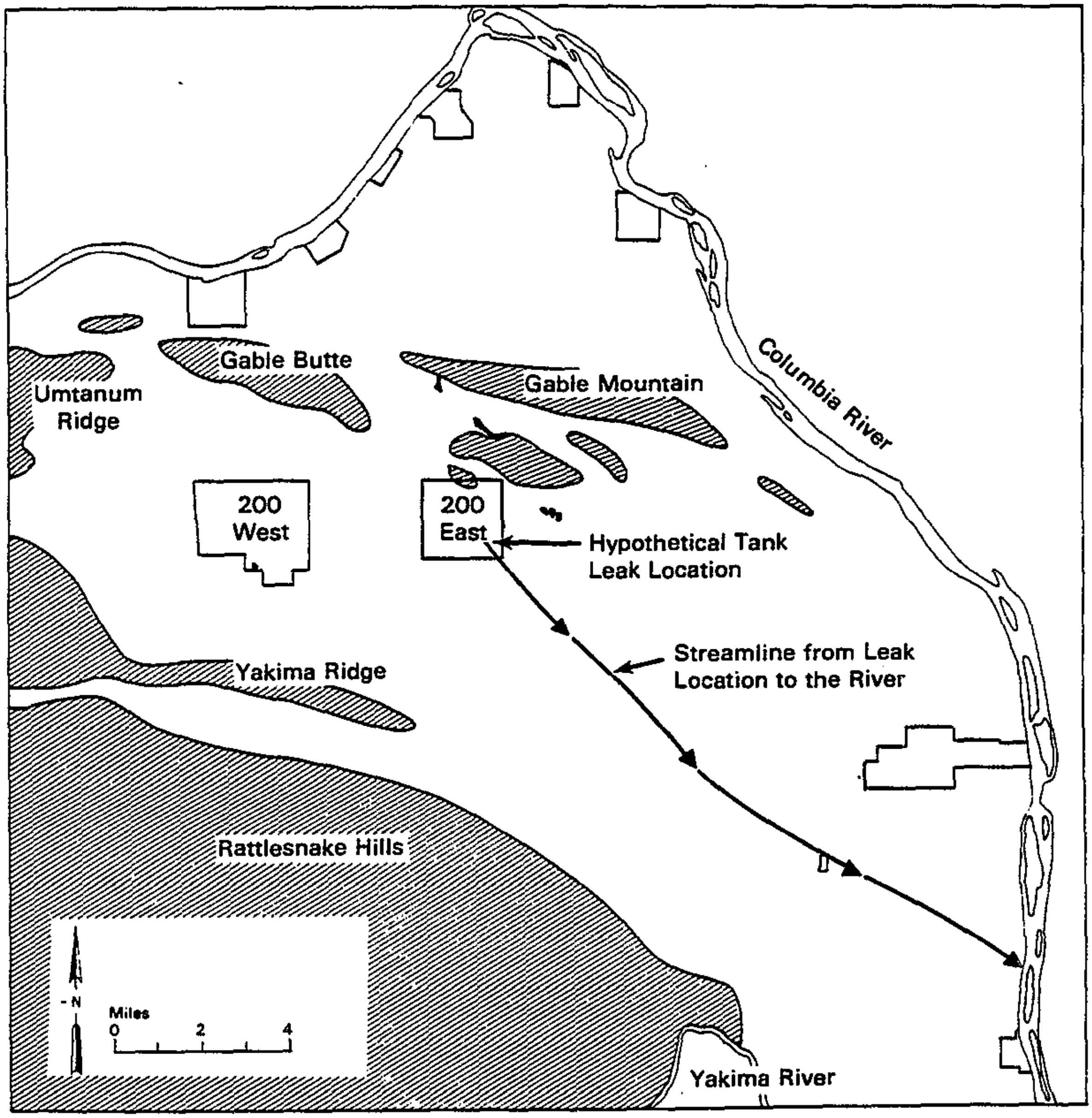

FIGURE 18. Steady Streamline from a Hypothetical Tank Leak in the 200-East Area to the Columbia River (after Arnett et al. 1977)

Arnett, Brown and Baca (1977) evaluated the impacts of subsurface contamination resulting from a series of hypothetical leaks involving Hanford high-level radioactive defense waste. Steady streamlines were based on a predicted 1990 water table surface. Arrival time and outflow quantity distributions were predicted with the MMT code at the Columbia River for different radionuclides from the hypothetical leaks in the 200-East Area.

Murthy et al. (1983) assessed the implications of removing interstitial liquids from single-shell tanks at the Hanford Site. Different scenarios were evaluated for release of the radionuclides and flow through the unsaturated zone to the ground water. The VTT model was applied to simulate 1980 ground-water conditions and provide input parameters for the MMT code. The steady streamlines illustrated in Figure 19 are from single-shell tank farm areas on the Hanford Site. The average ground-water travel times from these tank farm locations to the Columbia River are listed in Table 7. The results of transport predictions in terms of the contaminant arrival times and quantities at outflow locations along the river were used to calculate dose from the radionuclides.

Recently, the VTT and TRANSS codes were applied to evaluate alternatives for disposal of high-level defense wastes at the Hanford Site (DOE 1987). Radionuclide transport was investigated for different scenarios over a 10,000-year period beginning in the year 2150. Two climatic conditions were assumed to simulate post-Hanford conditions: 1) a drier climate with an upper bound of average annual ground-water recharge of 0.5 cm/yr, and 2) a wetter climate with an average annual recharge of 5 cm/yr. Thus, with no artificial recharge, the water table simulated for post-Hanford conditions was very much different from that observed for current conditions. Consequently, the flow paths for post-Hanford conditions (Figures 20 and 21) were also different from those predicted for current conditions. The travel times through the unsaturated and saturated zones to a well that is 5 km downgradient are listed in Table 8. These arrival times and contaminant outflow quantities at the 5-km well were used to estimate radionuclide dose.

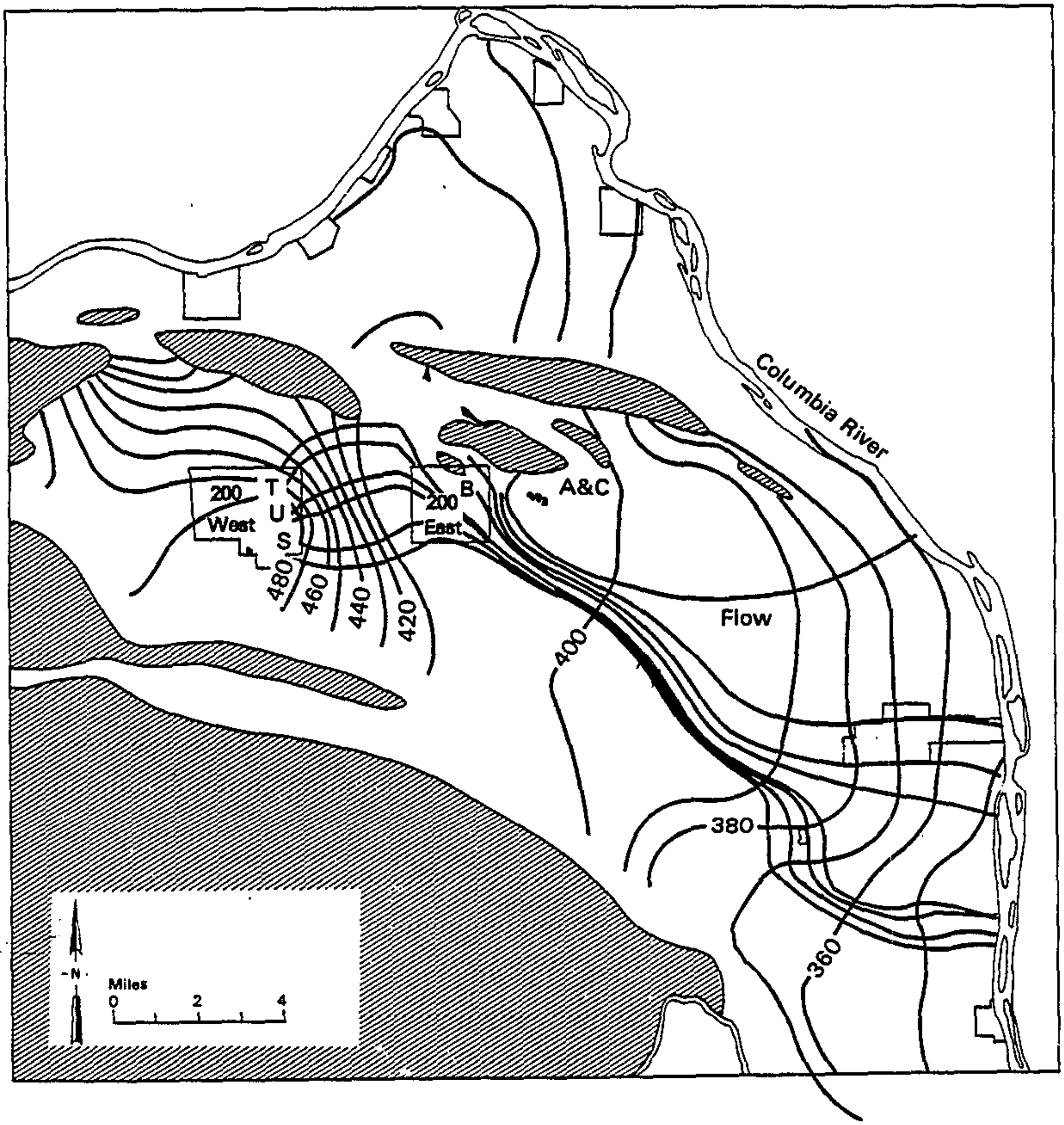

FIGURE 19. Water Table Contours (in feet above MSL) and Flow Tubes (defined by steady streamlines) from the Tank Farm Areas to the Columbia River (from Murthy et al. 1983)

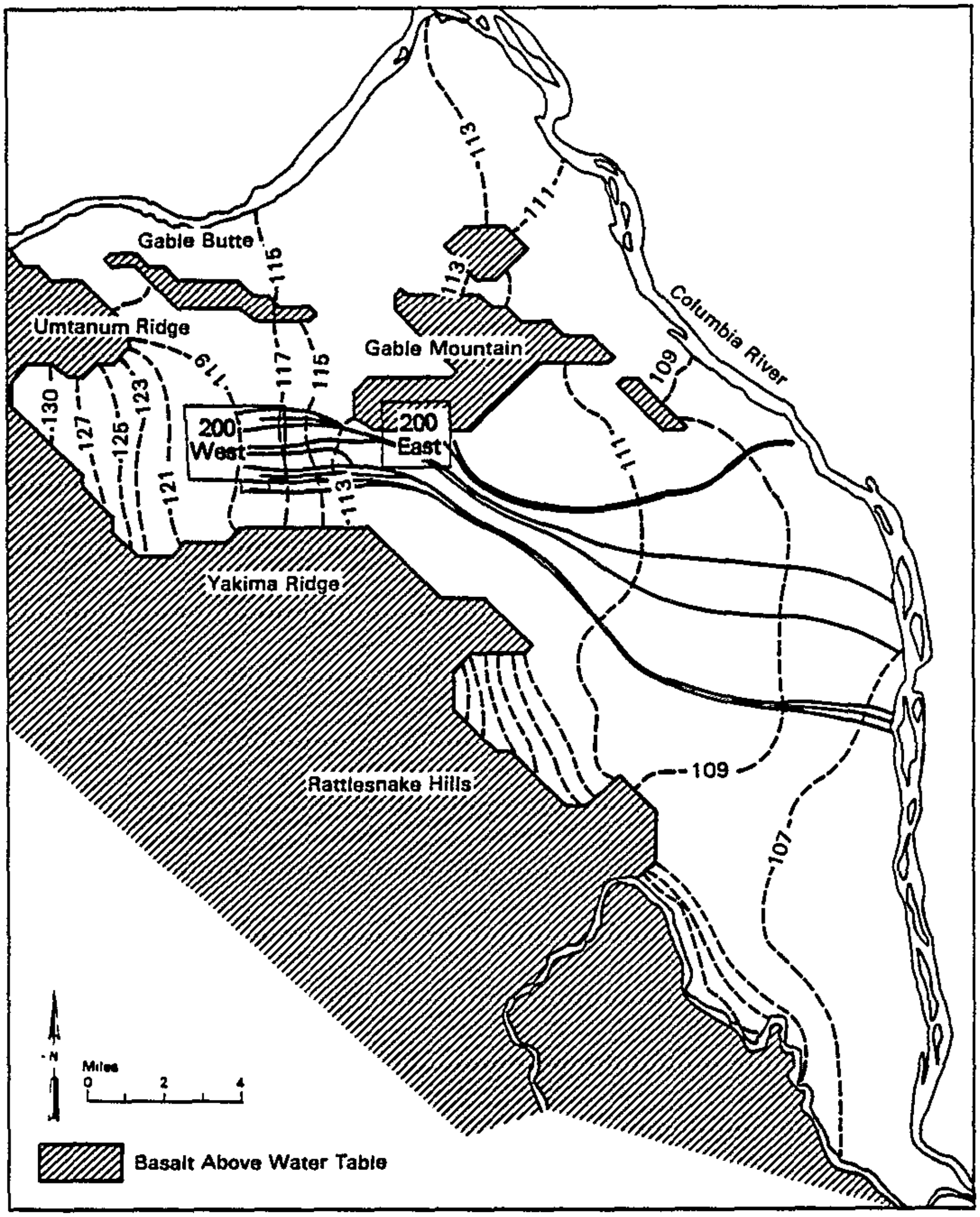

FIGURE 20. Ground-Water Contours (in meters above MSL) and Steady Streamlines from the 200 Areas Waste Sites to the Columbia River (assuming steady-state conditions, 0.5 cm/yr recharge, and no artificial recharge) (DOE 1987)

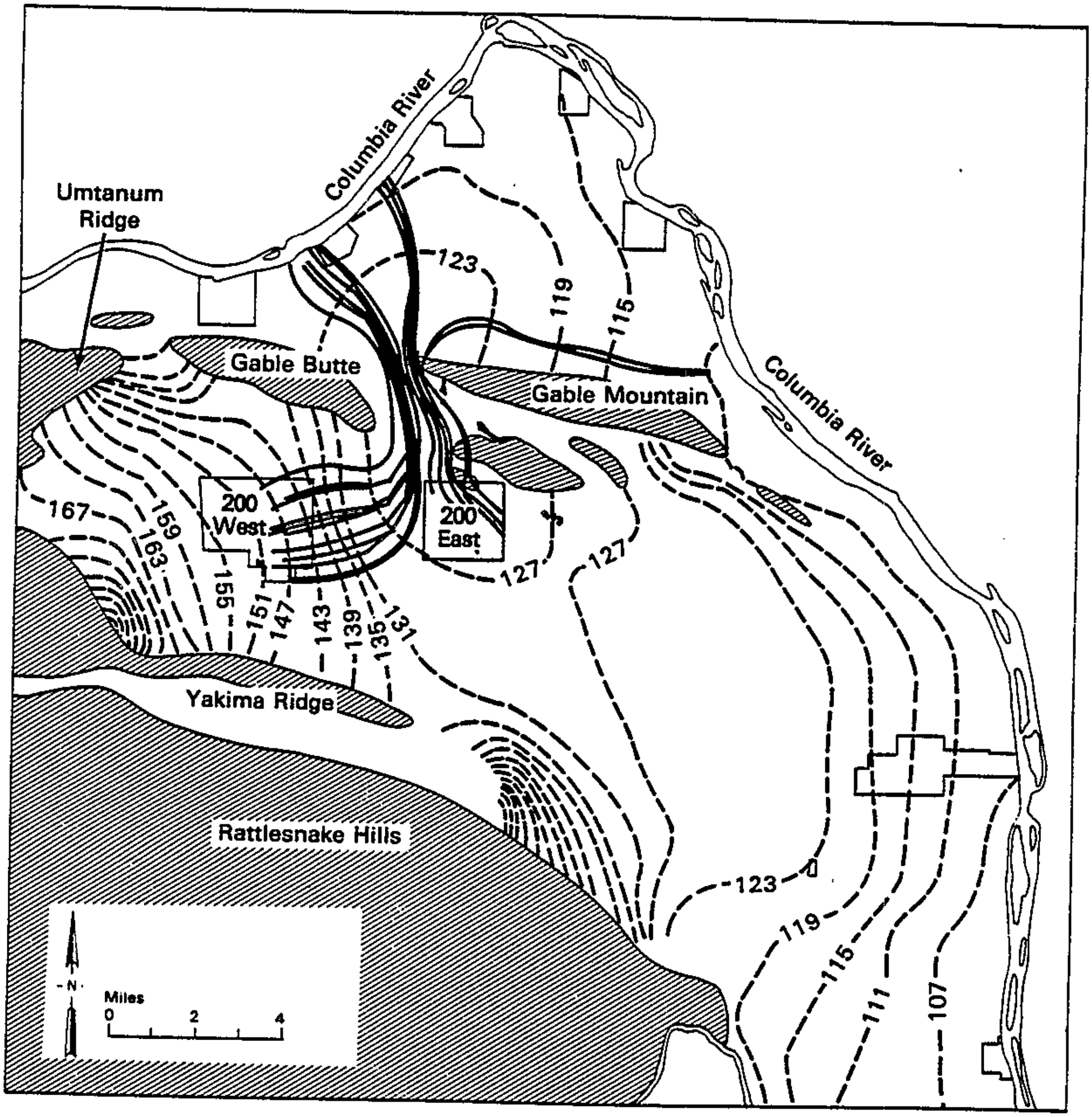

FIGURE 21. Ground-Water Contours (in meters above MSL) and Steady Streamlines from 200 Areas Waste Sites (assuming 5 cm/yr annual average recharge) (DOE 1987)

9 2 1 2 . 7 9 1 3 3 4

TABLE 7. Average Ground-Water Travel Times, Velocities, and Streamline Lengths (see Figure 19) from Tank Farm Locations (after Murthy et al. 1983)

Tank Farm	Average Travel Time, yr	Average Velocity, ft/yr	Average Path Length, ft
A, AX, C			
Tube 1	127.3	580.7	73,866
Tube 2	164.9	427.9	70,866
B, BX, BY	54.4	1,581.6	86,040
S, SX	88.7	1,326.9	117,625
T, TX, TY	190	651.6	123.843
U	124.8	943.6	118,724

TABLE 8. Time of Travel to a 5-km (3-mile) Well for the Different Scenarios Considered in the Hanford Defense Waste Environmental Impact Statement (DOE 1987)

Scenario	Travel Time in Vadose, yr	Travel Time in Aquifer to a 5-km Well, yr
0.5-cm/yr infiltration	~925	~2 to 25
5-cm/yr infiltration	~100	~1 to 5
Barrier functioning	$\sim 5 \times 10^3$ to 3×10^6	~1 to 15
Disruptive barrier failure	76	~1 to 5
Functional barrier failure	~4,200	~1 to 5

SUMMARY OF TRAVEL TIMES ESTIMATED AT THE HANFORD SITE

Travel times have beeh estimated at the Hanford Site since operations began in the 1940s. Most of the travel time estimates made during the 1940s and 1950s were relatively short, reflecting the limited ground-water monitoring data that were available. Tritium, one of the primary radionuclides used to evaluate travel times in the unconfined aquifer, was not known to be present in the aquifer until 1962. As the detection limit for tritium and other radionuclides improved, it was recognized that the tritium plume, defined by the 30 pCi/ml isopleth, reached the Columbia River around 1976 to 1979. Assuming that most of the tritium in the aquifer to the southeast of the 200-East Area is from discharge to the PUREX cribs, the average travel time for tritium from the PUREX cribs, based on monitoring data, is estimated to be 21 to 23 years. The USGS estimated an average arrival time of 13 years for tritium from the PUREX cribs at the river by assuming that most of the tritium was discharged to the ground after 1963. Consequently, travel time estimates based on monitoring data depend on the assumptions associated with release from sources and interpretation of the contaminant concentration data at wells.

Estimates of travel time at the Hanford Site based on local measurements have been made by extrapolating velocities measured at wells or between wells. These velocities have been determined from observations of contaminant movement, tracer tests, and borehole dilution tests. As demonstrated by Bierschenk (1959), the velocities extrapolated from local measurements may be different than the average velocity because ground-water and contaminant velocities vary along flow paths in the unconfined aquifer in response to changing aquifer properties and hydraulic gradients.

Ground-water flow and contaminant transport models of the Hanford unconfined aquifer have been used to estimate travel time from numerous starting locations in the aquifer, under different simulated flow conditions, and for ground water and many radionuclides and other contaminants. These estimates of travel time from locations in the 200 Areas range from several years to hundreds of years. Many of the travel times estimated with the Hanford Site models are for postulated future conditions. Therefore, travel times predicted with ground-water flow and contaminant transport models depend on the starting locations, water table conditions at the time of the prediction, and the flow path followed.

In general, travel times for ground water and contaminants in the unconfined aquifer to the Columbia River are longer for starting locations in the 200-West Area than for the 200-East Area, although they vary between individual starting locations. The flow paths from the 200-West Area to the river are longer than those from the 200-East Area for most conditions in the aquifer. The water table beneath the 200-West Area is located in the less permeable Ringold Formation, while the water table beneath the 200-East Area is currently located in the more permeable Hanford sediments.

Many of the investigations of proposed projects or actions at the Hanford Site have focused primarily on determining the impacts to the water table, flow paths, and travel times. However, more recent applications of the ground-water flow and contaminant transport models have considered the distribution of arrival times as well as the distribution of outflow quantities. These distributions have been used to estimate the dose to individuals at outflow locations such as the Columbia River.

A review of travel times estimated at the Hanford Site shows that a single travel time for the unconfined aquifer does not exist. Each estimate of travel time has been made for a specific starting location, under given conditions, and for ground water or a specific contaminant. In addition, recent applications have demonstrated that the ground-water flow and contaminant transport models at the Hanford Site can be applied to predict the contaminant arrival and contaminant outflow distributions for evaluating the consequences of ground-water contamination.

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IDENTIFICATION OF FUTURE NEEDS

Nelson (1978a,b,c,d) states that the contaminant quantities, arrival times, and outflow locations, which are necessary for evaluating the consequences of ground-water contamination, can be related in two ways. The first and most general approach is to use the outflow location as the predominant variable. In this approach, a location/arrival time distribution is defined to give the location at which contamination reaches an outflow boundary as a function of time. A location/outflow quantity distribution, which can be used to estimate the quantities of a contaminant reaching the accessible environment, is also defined. This approach can be used for either steady-state or transient ground-water flow systems. The second approach uses the cumulative quantity of water or contaminant outflow as the predominant variable. The second approach is less general than the first, because it is restricted to analysis of steady-flow systems, but is simpler to apply. In the second approach, outflow quantity/arrival time and outflow quantity/location distributions are defined.

Ground-water contamination in the unconfined aquifer at the Hanford Site needs to be evaluated in terms of outflow locations, distributions of arrival times, and outflow quantities. In the process of evaluating contamination at the site with these three components, confusion about travel times in the unconfined aquifer can be avoided in the future.

As described in the section on Review of Previous Travel Time Estimates at the Hanford Site, inspection of more than 40 years of ground-water monitoring data demonstrates that waste disposal in the operating areas has resulted in ground-water contamination by radioactive and chemical constituents. Although the monitoring data, primarily for tritium, have been reviewed and interpreted to estimate travel times, a comprehensive review of the historical records is needed.

Establishing arrival time and outflow quantity distributions for contaminants in the unconfined aquifer will require additional work. This will consist of reviewing existing ground-water monitoring data, characterizing the unconfined aquifer in three dimensions, and modeling ground-water flow and contaminant transport based on the three-dimensional characterization. The three-dimensional characterization will provide a basis for the models, which may be one-, two-, or three-dimensional, depending on which is appropriate for each specific application. In addition, release of contaminants to the soil column and the ground water must be further characterized to estimate travel times.

In their review of previous work at the Hanford Site, the USGS (1987) made recommendations for collecting geohydrologic and geochemical data from the unconfined aquifer in three dimensions. They also suggested that ground-water flow and contaminant transport in the unconfined aquifer be modeled in three dimensions.

Currently, the unconfined aquifer is characterized and monitored in two dimensions, except at a few hazardous waste sites. These hazardous waste sites occupy only a small portion of the total area of the Hanford Site. In addition, the effects of vertical variations in permeability, hydraulic head, contaminant mobility parameters, and contaminant concentrations are not considered in the two-dimensional approach. These characteristics of the unconfined aquifer and the existing contaminants must be determined in three dimensions to evaluate the environmental consequences of ground-water contamination.

Ground-water flow and contaminant transport models should be applied to define the arrival time and contaminant quantity distributions for the unconfined aquifer at the Hanford Site. These distributions can then be evaluated with respect to their usefulness for determining the consequences of ground-water contamination in the unconfined aquifer and for communicating this information to decision makers and the public.

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